Water Quality Report: 2014

Wachusett Reservoir Watershed

March 2015

Massachusetts Department of Conservation and Recreation
Division of Water Supply Protection
Office of Watershed Management

ABSTRACT

The Department of Conservation and Recreation, Division of Water Supply Protection, Office of Watershed Management manages and maintains a system of watersheds and reservoirs to provide pure water to the Massachusetts Water Resources Authority (MWRA), which in turn supplies drinking water to approximately 2.2 million people and thousands of industrial users in 51 communities.

Water quality sampling and watershed monitoring make up an important part of the overall mission of the Division of Water Supply Protection. These activities are carried out by Environmental Quality Section staff at Wachusett Reservoir in West Boylston and at Quabbin Reservoir in Belchertown. This report is a summary of 2014 water quality data from the Wachusett Reservoir tributaries and reservoir. A report summarizing 2014 water quality data from the Quabbin and Ware River watersheds is also available from the Division.

ACKNOWLEDGEMENTS:

This report was prepared by the Department of Conservation and Recreation Division of Water Supply Protection Office of Watershed Management. Authors are Lawrence Pistrang, Environmental Analyst, and Jamie Carr, Aquatic Biologist. The sampling station map was produced by GIS analyst Craig Fitzgerald using the most recent data. Internal review was provided by Patricia Austin and John Scannell. Steve Sulprizio, Jamie Carr, Joy Trahan-Liptak, David Getman, and Daniel Crocker collected the samples and were responsible for all field measurements. Plankton samples were analyzed by Jamie Carr and Joy Trahan-Liptak. Turbidity analysis was done by Steve Sulprizio, David Getman, Daniel Crocker, or Patricia Austin. All other lab analyses (bacteria, nutrients, and metals) were performed by MWRA staff. John Scannell is the Regional Director of the Wachusett/Sudbury Operational Section and Jonathan Yeo is the Director of the Division of Water Supply Protection.

The DCR/DWSP Office of Watershed Management once again would like to thank the staff and management of the MWRA Deer Island Lab for preparing and delivering sample bottles and performing all nutrient and metal analyses during the year. They also thank the MWRA staff at the Southborough Lab for completing all routine and non-routine *E. coli* and fecal coliform analyses during the year.

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1.0 INTRODUCTION

The Department of Conservation and Recreation Division of Water Supply Protection Office of Watershed Management (the Division) was established by Chapter 372 of the Acts of 1984. The Division was created to manage and maintain a system of watersheds and reservoirs and provide pure water to the Massachusetts Water Resources Authority (MWRA), which supplies drinking water to 2.2 million people and thousands of industrial users in 51 communities.

The Federal Surface Water Treatment Rule requires filtration of surface water supplies unless numerous criteria are met, including development and implementation of a detailed watershed protection plan. The Division and the MWRA have a joint waiver from the filtration requirement and continue to aggressively manage the watershed in order to maintain this waiver. Water quality sampling and field inspections help identify tributaries with water quality problems, aid in the implementation of the most recent watershed protection plan, and ensure compliance with state and federal water quality criteria for public drinking water supply sources. Bacterial monitoring of the reservoir and its tributaries provide an indication of sanitary quality and help to protect public health. Division staff also sample to better understand the responses of the reservoir and its tributaries to a variety of physical, chemical, and biological inputs, and to assess the ecological health of the reservoir and the watershed.

Watershed tributaries and reservoirs comprise the two basic components of the water supply system. Each component requires a specialized program of monitoring activities and equipment suited to their unique characteristics and environmental settings.

Routine water quality samples for bacteria, specific conductance, turbidity, and temperature were collected from nineteen stations on eighteen tributaries. Nutrient samples were collected monthly from nine of these stations. Stormwater sampling was done monthly at 2-4 locations to supplement routine sampling. Samples were occasionally collected from additional locations to investigate water quality problems discovered during environmental assessment investigations. Results from all tributary sampling are discussed in Section 3.0.

The Wachusett Reservoir was sampled 1-2 times per week to monitor plankton concentrations, predict potential taste and odor problems, and recommend algaecide treatment as needed. Temperature, pH, dissolved oxygen, and specific conductance profiles were measured weekly in conjunction with plankton sampling. Quarterly nutrient samples were collected in May, July, October, and December at three depths from three reservoir stations. Fecal coliform samples were collected monthly or more frequently from the reservoir surface to document the relationship between bacteria and roosting populations of waterfowl on the reservoir. Results from all reservoir monitoring efforts are discussed in Section 4.0.

All bacteria, conductivity, turbidity, nutrient, and precipitation data for the past seventeen years are stored in EXCEL spreadsheets on the Division server at John Augustus Hall in West Boylston. An EXCEL spreadsheet of plankton data is also maintained. All data generated during tributary and reservoir water quality testing are discussed by parameter in sections 3.1 – 4.4 and will be made available upon request.

2.0 DESCRIPTION OF MONITORING PROGRAMS

Division staff collected routine water quality samples from nineteen stations on eighteen tributaries and from three stations on the Wachusett Reservoir in 2014. Stations are described in Tables 1 and 2 and sampling locations shown on Figures 1-3 on pages 3-6. Additional stations were sampled to support special studies or potential enforcement actions. Storm events were sampled on nine separate occasions at four locations. Some samples were analyzed in-house including 740 turbidity samples and 140 reservoir plankton samples. A total of 1,481 physiochemical measurements (temperature and specific conductance) were done in the field at tributary stations, and 36 water column profiles (temperature, specific conductance, dissolved oxygen, percent oxygen saturation, chlorophyll a, pH) recorded on the reservoir. In addition, 1,140 bacteria samples were collected and delivered to the MWRA Southborough laboratory for *E. coli* or fecal coliform analysis, and approximately 400 samples were collected and shipped to the MWRA Deer Island laboratory for about 2,800 analyses of nutrients and other parameters.

2.1 TRIBUTARY MONITORING

Each tributary station was visited weekly or every other week throughout the entire year, although samples were not collected at some stations during low flow or no-flow conditions in the summer months. Temperature and specific conductance were measured in the field using a YSI Model 30 conductivity meter. Discrete samples were collected for analysis of *E. coli* and turbidity. All *E. coli* samples were delivered to the MWRA Southborough Lab for analysis. Turbidity samples were analyzed at the DCR West Boylston Lab using a HACH 2100N meter.

Nutrient samples were collected monthly from nine stations (shown on Table 1) and analyzed at the MWRA Deer Island Lab for total phosphorus, ammonia, nitrate-nitrogen, nitrite-nitrogen, UV-254, total organic carbon, and total suspended solids. Reactive phosphorus samples were collected monthly from Gates Brook and the Stillwater and Quinapoxet Rivers. All sample collections and analyses were conducted according to Standard Methods for the Examination of Water and Wastewater 22nd Edition. Depth was recorded manually or using automated depth sensors at six of the nutrient stations in order to calculate flow using rating curves developed by the USGS and modified by DCR Environmental Quality staff. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers was obtained from continuous recording devices installed by the USGS.

Precipitation data from NOAA weather stations in Worcester and Fitchburg, from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden, from the MWRA rain gage in Clinton, and from a DCR rain gage in West Boylston were collected daily to help interpret water quality changes and determine if these were impacted by precipitation events.

FIGURE 1

WACHUSETT WATERSHED TRIBUTARY SAMPLING STATIONS

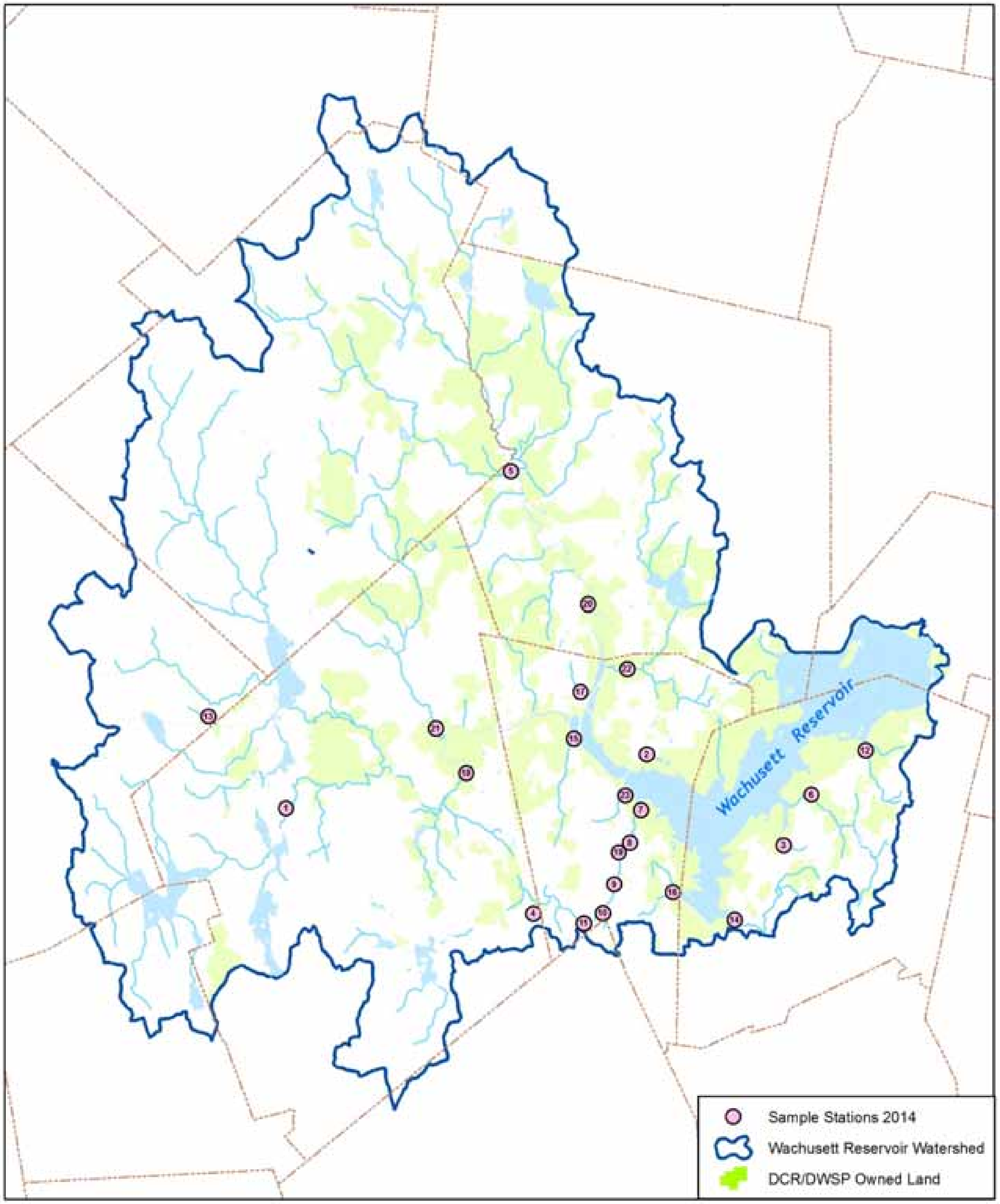


TABLE 1

WACHUSETT TRIBUTARY SAMPLING STATIONS (2014)

STATION	LOCATION	FREQUENCY
1. Asnebumskit Brook (Princeton)	upstream of Princeton Street, Holden	W
2. Beaman Pond Brook (2)	Route 110, W. Boylston (homes)	W
3. Boylston Brook	Route 70, Boylston	W
4. Cook Brook (Wyoming)	Wyoming Street, Holden	W
5. East Wachusett Brook (140)	Route 140, Sterling	W
6. French Brook (70)	Route 70, Boylston	W, M
7. Gates Brook (1)	Gate 25, West Boylston	W, M
8. Gates Brook (2)	Route 140, West Boylston	not sampled
9. Gates Brook (4)	Pierce Street, West Boylston	W
10. Gates Brook (6)	Lombard Avenue, West Boylston	not sampled
11. Gates Brook (9)	Woodland Street, West Boylston	not sampled
12. Hastings Cove Brook	Route 70, Boylston	not sampled
13. Jordan Farm Brook	Route 68, Rutland	W
14. Malagasco Brook	West Temple Street, Boylston	W, M
15. Malden Brook	Thomas Street, West Boylston	W, M
16. Muddy Brook	Route 140, W West Boylston	W, M
17. Oakdale Brook	Waushacum Street, West Boylston	W
18. Quinapoxet River (Canada Mills)	Canada Mills, Holden	W, M
19. Scarlett Brook	Worcester Street, West Boylston	W
20. Stillwater River (SB)	Muddy Pond Road, Sterling	W, M
21. Trout Brook	Manning Street, Holden	W
22. Waushacum Brook (Prescott)	Prescott Street, West Boylston	W, M
23. West Boylston Brook	Gate 25, West Boylston	W, M

W = weekly (bacteria, temperature, specific conductance, turbidity)
M = monthly (nutrients)

2.2 RESERVOIR MONITORING

Temperature, dissolved oxygen concentration and percent saturation, specific conductance, and pH profiles were recorded weekly during stratified conditions at Station 3417 (Basin North) in conjunction with routine plankton monitoring. Samples were collected quarterly (May, July, October, December) at Station 3417 (Basin North), Station 3412 (Basin South) and Thomas Basin. At each station, samples were collected from the epilimnion, metalimnion, and hypolimnion and analyzed for nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, silica, UV-254, and alkalinity. (See Table 2 and Figure 2 for locations). All samples were analyzed at the MWRA Lab at Deer Island (see Section 4.0 for complete discussion).

TABLE 2

WACHUSETT RESERVOIR SAMPLING STATIONS (2014)

STATION	LOCATION	FREQUENCY
A. 3409 (Reservoir)	adjacent to Cosgrove Intake	W
B. 3417 (Reservoir – Basin North)	mid reservoir by Cunningham Ledge	W, Q
C. 3412 (Reservoir – Basin South)	mid reservoir off Scar Hill Bluffs	Q
D. Thomas Basin (Reservoir)	Thomas Basin	Q

W = weekly (temperature, conductivity, plankton, and water column profiles at Cosgrove or 3417)
Q = quarterly (plankton, profiles, nutrients)

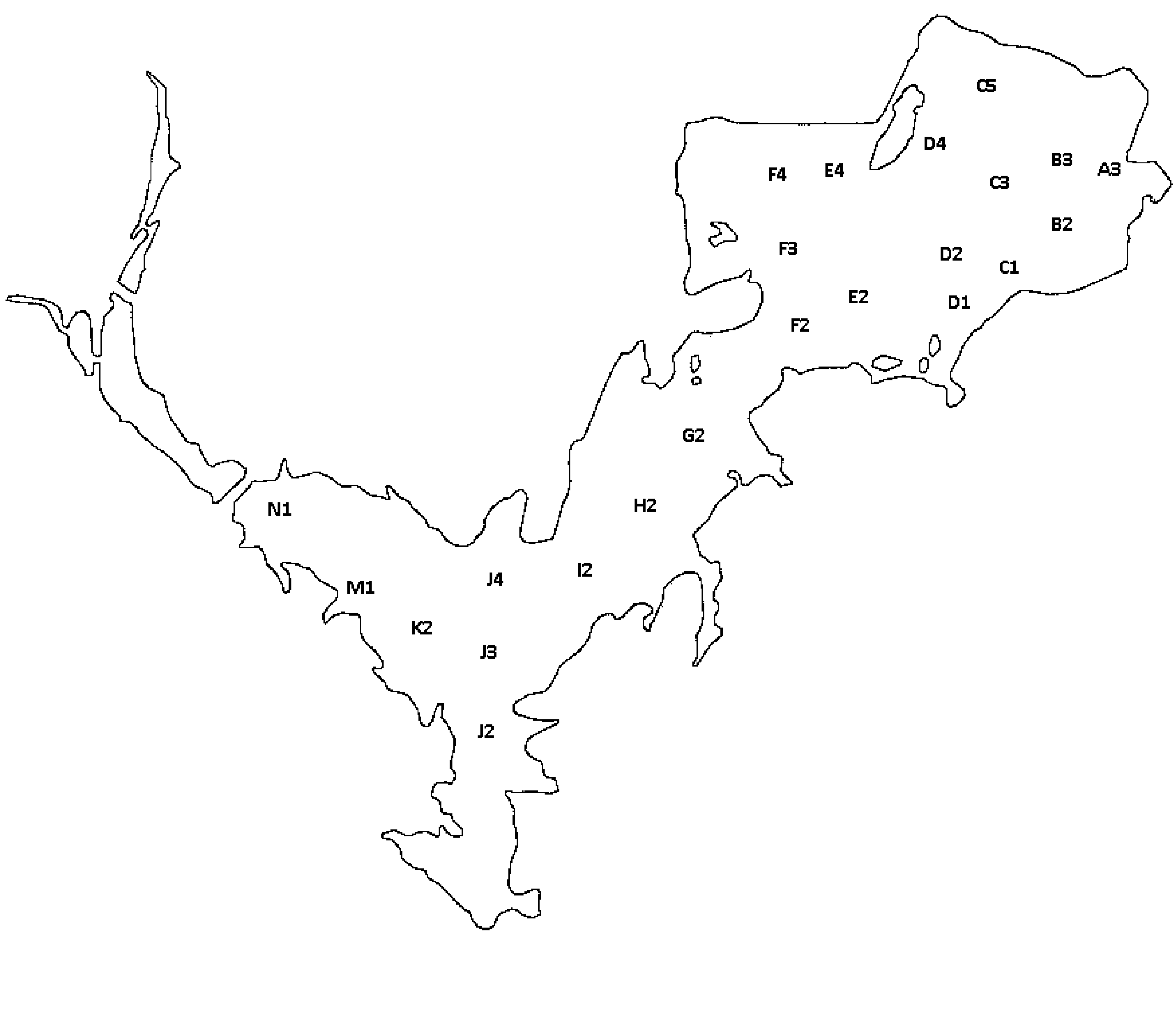
FIGURE 2

RESERVOIR NUTRIENT AND PHYTOPLANKTON SAMPLING STATIONS

MWRA personnel collected a regulatory fecal coliform sample seven times per week from the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough. Fecal coliform samples were collected by Division staff from 23 reservoir surface stations (Figure 3) once or twice per month.

FIGURE 3

RESERVOIR TRANSECT STATIONS



3.0 RESULTS OF TRIBUTARY MONITORING PROGRAM

3.1 BACTERIA

The Massachusetts Class A surface water quality standards use *E. coli* as an indicator organism. The statutory limit is "a geometric mean not to exceed 126 *E. coli* colonies per 100 mL and with no single sample to exceed 235 colonies per 100 mL". The geometric mean of 126 colonies per 100 mL was not exceeded at any tributary station during 2014. The same was true in 2008, 2009, and 2013, although the limit was exceeded at Gates Brook 4 in 2010, at both Gates Brook 4 and Gates Brook 6 in 2011, and at Gates Brook 4, Gates Brook 6, and Oakdale Brook in 2012. Every station exceeded the single sample limit of 235 colonies per 100 mL in 2010, 2011, and 2012, but four stations (Cook Brook, Trout Brook, East Wachusett Brook, and Waushacum Brook) met the standard in 2013, and both Trout Brook and Waushacum Brook met the standard again in 2014 (Table 3).

TABLE 3

***E. coli* - TRIBUTARIES**
(MPN/100 mL)

STATION	GMEAN (2014)	GMEAN (2013)	GMEAN (2012)	GMEAN (2011)	%>235 (2014)	%>235 (2013)	%>235 (2012)	%>235 (2011)
Asnebumskit (Princeton)	64	40	45	37	23	10	24	16
Beaman Pond Brook 2	33	34	48	49	7	10	19	18
Boylston Brook	26	72*	33	31	13	24	17	10
Cook Brook (Wyoming)	34	18	21	20	20	0	10	10
East Wachusett (140)	19	11	18	20*	8	0	6	8
French Brook (70)	41*	23	38	37	12	4	14	8
Gates Brook (1)	31	26	29	54*	10	14	10	16
Gates Brook (4)	110	90	**225***	**180**	28	28	51	46
Jordan Farm Brook	40*	15	19	28	12	4	6	12
Malagasco Brook	27	18	25	32*	6	6	8	10
Malden Brook	28	20	27	36	6	2	10	8
Muddy Brook	28	20	20	29*	4	2	2	10
Oakdale Brook	31	40	**143***	75	12	12	41	27
Quinapoxet River (C.Mills)	36	27	37	37	8	4	8	6
Scarlett Brook	38	35	50*	45	10	12	22	10
Stillwater River (SB)	32	30	42	49	6	6	10	16
Trout Brook	23	12	16		0	0	2	
Waushacum (Prescott)	34	19	23	32	0	0	4	10
West Boylston Brook	82	56	54	73	22	14	14	22

*highest annual geometric mean (2006-2014)

Bacteria samples collected from the nineteen tributary stations during 2014 contained a wide range of *E. coli* concentrations, from less than 10 MPN/100mL in seventeen percent of all samples to a high of 12,000 MPN/100mL in Asnebumskit Brook during a heavy summer rain event. In previous years, many of the highest concentrations were recorded during or following rain events, and this was the case again in 2014. Eighteen samples that exceeded 1000 MPN/100mL were collected during or following wet weather from eleven different sites throughout all four seasons. Only three samples that exceeded 1000 MPN/100mL were collected during dry weather, both from locations with known or suspected wildlife presence (Asnebumskit and West Boylston Brooks).

Annual geometric mean concentrations increased at sixteen of nineteen stations, although some of the increases were very small. Almost all *E. coli* concentrations in 2013 were below the average of the previous eight years and several were the lowest in the period, so the widespread increase in 2014 is not unexpected. French Brook and Jordan Farm Brook had their highest ever annual geometric mean in 2014, however, and eleven of nineteen stations were above the average of the previous nine years.

The geometric mean of the 755 tributary samples collected in 2014 was 37 MPN/100mL. This was higher than in 2013 but the number of sample stations and samples collected in 2014 were less than in previous years and a direct comparison may not be appropriate.

Variable water quality may be caused by fluctuations in pollutant inputs or weather conditions, including changes in the timing, frequency, and magnitude of precipitation events. These are more commonplace than before due to climate change. Numerous potential sources of bacteria and the increased likelihood of short-term weather variations make it difficult to interpret changes in water quality parameters over the short term and it is more informative to examine long term trends in water quality. Reliable data from many Wachusett watershed tributaries now extend over a period of more than twenty years and long term trends suggest that conditions at most locations remain stable or have improved. The next detailed assessment of long term trends will be published in early 2019.

TABLE 4

IMPACTS OF >0.2" RAINFALL ON OVERALL *E. coli* CONCENTRATIONS

	dry 2014	**wet 2014**	**dry 2008-2013**	**wet 2008-2013**
annual geometric mean (MPN/100mL)	27	90	19 - 31	54 - 148
% samples <126 MPN/100mL	87	58	82 - 92	45 - 66
% samples >235 MPN/100mL	6	25	3 - 10	20 - 41

Rain events continue to be linked to poor water quality and the difference between dry weather and wet weather samples is clearly illustrated above in Table 4. Annual geometric mean of all dry weather samples is less than one third the annual geometric mean of wet weather samples. The percentage of wet weather samples that contained more than 235 MPN/100mL was more than four times higher than the percentage of dry weather samples.

Impacts from rain events are often more significant in subbasins with a high concentration of impervious surfaces or agricultural operations. The 2012 geometric means of wet weather samples from Gates, Boylston, Beaman Pond, and French Brooks were 11-23 times higher than dry weather samples, while differences at other sampling stations were much less. None of the stations in 2013 had a wet weather geometric mean more than five times higher than their dry weather mean, however, and many were only 1-2 times higher. Wet weather geometric means in Boylston, Jordan Farm, French, and Gates Brooks during 2014 were five to nine times higher than their dry weather means, but the differences were considerably less than in 2012. Some of the positive changes could have been due in part to below average amounts of rainfall during the summer, but it is believed that much of the change in the relationship between wet weather and dry weather metrics can be attributed to improvements in stormwater management.

TABLE 5

IMPACTS OF >0.2" RAINFALL ON *E. coli* CONCENTRATIONS AT EACH STATION
(PERCENTAGE OF DRY AND WET SAMPLES >126 MPN/100 mL, >235 MPN/100 mL)

	% dry>126	% wet>126	% dry>235	% wet>235
Asnebumskit Brook (Princeton)	40.0%	33.3%	25.0%	16.7%
Beaman Pond Brook 2	18.2%	0.0%	9.1%	0.0%
Boylston Brook	3.8%	61.5%	3.8%	30.8%
Cook Brook (Wyoming)	15.0%	40.0%	15.0%	40.0%
East Wachusett Brook (140)	10.0%	20.0%	10.0%	0.0%
French Brook (70)	13.9%	42.9%	5.6%	28.6%
Gates Brook (1)	0.0%	35.7%	0.0%	35.7%
Gates Brook (4)	30.6%	78.6%	16.7%	57.1%
Jordan Farm Brook	20.0%	40.0%	5.0%	40.0%
Malagasco Brook	8.3%	35.7%	0.0%	21.4%
Malden Brook	5.6%	35.7%	0.0%	21.4%
Muddy Brook	2.8%	21.4%	0.0%	14.3%
Oakdale Brook	15.0%	40.0%	5.0%	40.0%
Quinapoxet River (Canada Mills)	8.3%	50.0%	0.0%	28.6%
Scarlett Brook	5.6%	50.0%	0.0%	35.7%
Stillwater River (SB)	5.6%	28.6%	2.8%	14.3%
Trout Brook	0.0%	40.0%	0.0%	0.0%
Waushacum Brook (Prescott)	13.9%	42.9%	0.0%	0.0%
West Boylston Brook	36.1%	42.9%	22.2%	21.4%

Not all stations exhibit a clear difference between dry weather and wet weather bacteria concentrations. Water quality in Asnebumskit, Beaman Pond, and West Boylston Brooks is worse during dry weather than in wet weather (Table 5).

Tributary water quality often shows clear seasonal differences during both dry and wet weather as illustrated in Table 6. Bacteria numbers tend to be lower in the winter and spring months (December through May), with wet weather concentrations about two to five times higher than dry weather concentrations. Summer numbers are usually much higher than in the winter or spring, likely caused by low flow conditions that concentrate bacteria or large storm events that increase loading, and wet weather concentrations remain about two to three times higher than dry weather concentrations. Fall concentrations are elevated or not depending upon the amount and timing of precipitation. Differences between wet weather and dry weather concentrations are usually much more pronounced in the fall than in other seasons, but this was not the case in 2013.

Regardless of land use or of the timing, frequency, and magnitude of precipitation events, it remains clear that water quality is negatively impacted by unmanaged stormwater. Samples were collected during or within 24 hours of storm events on 20 of 76 routine weekly sampling dates. The Division also supplements routine weekly sampling with focused monthly stormwater sampling on 2-4 tributaries to enable calculation of pollutant loadings and helps to better understand the impacts from storm events. Use of water quality modeling has also been initiated to assist in the effort. Additional analysis and interpretation of stormwater impacts on water quality is included in Section 3.6.

TABLE 6

SEASONAL EFFECT ON *E. coli* CONCENTRATIONS
(MPN/100 mL)

	WINTER	SPRING	SUMMER	FALL
geometric mean (2010)	19	20	124	59
geometric mean (2011)	23	27	100	39
geometric mean (2012)	24	29	93	42
geometric mean (2013)	17	24	68	25
geometric mean (2014)	20	24	79	48
geometric mean – dry (2010)	17	17	77	41
geometric mean – dry (2011)	18	21	80	24
geometric mean – dry (2012)	20	17	69	29
geometric mean – dry (2013)	19	19	55	26
geometric mean – dry (2014)	15	18	59	35
geometric mean – wet (2010)	47	35	235	255
geometric mean – wet (2011)	74	59	253	466
geometric mean – wet (2012)	108	96	179	300
geometric mean – wet (2013)	8	61	109	23
geometric mean – wet (2014)	47	59	137	149

3.2 FLOW

Flow monitoring has been done at a number of locations throughout the watershed for the past two decades using both manual and automated measurements. The USGS was responsible for the development and maintenance of stage/discharge relationships at these sites, but occasional shifts to stream channels plus an extended period with very infrequent field visits led to questions about the accuracy of the data. The USGS continues to operate three stations using continuous monitoring, but responsibility for all other sites was transferred to the DCR towards the end of 2011.

Manual measurements of stream depth are made each week at seven stations using visual observation of staff gages. Six of the stations have been monitored for many years; documentation of flow in Trout Brook began in 2014. Direct measurement of flow at a range of depths is done several times during the year using a FlowTracker handheld acoustic Doppler velocity meter to develop and calibrate accurate stage-discharge relationships. Water depth and velocity measurements are usually taken about 50-100 feet upstream from each staff gage in an area with a uniform stream bed. Reliable stage-discharge relationships at five stations allow the use of easily acquired stream depths to quickly estimate flow. The stage-discharge relationships at Muddy Brook and Trout Brook remain under development and no flow data are available.

Three other stations utilize continuous monitoring equipment maintained by the USGS to collect and transmit real time data every 10-15 minutes. Continuous data from the Stillwater and Quinapoxet Rivers have been collected since 1994. Flow data from Gates Brook were collected manually from 1994 until December 2011 when a flow monitoring sensor was installed. Installation of a new bridge over Gates Brook prevented flow measurements for almost four months in 2014 (August-November) and a new stage-discharge relationship is being developed.

TABLE 7

TRIBUTARY FLOW – WACHUSETT WATERSHED

	day max	day min	day ave	month max	month min	yearly total
QUINAPOXET	937 cfs	2.9 cfs	55.4 cfs	401 million ft^3	23 million ft^3	1.7 billion ft^3
STILLWATER	843 cfs	2.7 cfs	47.4 cfs	323 million ft^3	10.4 million ft^3	1.5 billion ft^3
GATES	48.0 cfs*	1.1 cfs*	4.7 cfs*	21.6* million ft^3	5.9* million ft^3	n/a*
WAUSHACUM	67.0 cfs	0.2 cfs	8.6 cfs	83.4 million ft^3	982,000 ft^3	271 million ft^3
W. BOYLSTON	2.4 cfs	0.06cfs	0.4 cfs	3.5 million ft^3	177,000 ft^3	12.4 million ft^3
MALAGASGO	5.3 cfs	0.05 cfs	0.9 cfs	7.7 million ft^3	168,000 ft^3	30.0 million ft^3
MALDEN	17.7 cfs	0.4 cfs	3.8 cfs	25.8 million ft^3	1.9 million ft^3	119 million ft^3
FRENCH	20.2 cfs	0.15 cfs	3.7 cfs	31.3 million ft^3	429,000 ft^3	118 million ft^3

*data available from January-July only

Daily and monthly flows varied widely at all locations and illustrate the need for regular and frequent flow monitoring (Table 7). Daily flows in the tributaries ranged from near zero to more than 900 cfs. Average daily flows were 1-5 cfs in most tributaries but much higher in the two rivers. Variations in daily and monthly instantaneous and total flow were dramatic, with maximum values more than 300 times greater than minimum values.

3.3 NUTRIENTS

Samples for nitrate-nitrogen, nitrite-nitrogen, ammonia, total phosphorus, total organic carbon, total suspended solids, and UV-254 were collected monthly from nine tributary stations with available flow data and analyzed at the MWRA Deer Island Lab using methods with low detection limits. UV-254 samples were collected weekly from the Quinapoxet and Stillwater Rivers. Samples were preserved according to standard methods. Depth measurements were taken at six stream stations to determine flow using rating curves developed by the USGS and modified by DCR Environmental Quality staff. Daily flow was monitored in the Stillwater and Quinapoxet River and in Gates Brook using continuous USGS recording devices. All data are available upon request.

High concentrations of nitrates can cause significant water quality problems including dramatic increases in aquatic plant growth and changes in the plants and animals that live in aquatic environments. High concentrations eventually lead to changes in dissolved oxygen and temperature. Excess nitrates can become toxic to warm-blooded animals at very high concentrations (10 mg/L) or higher) but never reach these values in the Wachusett watershed. Sources of nitrates include runoff from agricultural sites and fertilized lawns, failing on-site septic systems, and some industrial discharges.

Annual mean nitrate-nitrogen concentrations in the nine tributaries ranged from 0.045 mg/L NO_3-N to 1.14 mg/L NO_3-N (Table 8), with individual measurements from below detection to 1.72 mg/L NO_3-N. Nitrate concentrations in West Boylston and Gates Brooks are higher than in other brooks, but remain considerably lower they were 5-10 years ago.

TABLE 8

NITRATE-NITROGEN CONCENTRATIONS (mg/L)

STATION	Muddy	French	Gates	Malagasco	Malden	Waushacum	W. Boylston	Stillwater	Quinapoxet
ave2014	0.135	0.167	0.86	0.583	0.443	0.045	1.14	0.136	0.251
ave2013	0.144	0.159	0.92	0.709	0.550	0.040	1.39	0.163	0.259
ave2012	0.098	0.127	0.80	0.489	0.432	0.036	1.17	0.140	0.222
ave2011	0.089	0.154	0.93	0.426	n/s	n/s	1.09	0.156	0.185
ave2010	0.105	0.135	1.01	0.634	0.471	n/s	1.57	0.156	0.256
ave2009	0.072	0.105	1.03	0.504	0.403	n/s	1.25	0.122	0.196
ave2008	0.132	0.071	1.04	0.513	0.452	n/s	1.69	0.146	0.321
ave2007	0.113	0.094	1.10	0.735	0.423	n/s	2.05	0.178	0.325

Nitrite-nitrogen was rarely detected during routine sampling. Only two of the 108 samples collected in 2014 contained more than the detection limit of 0.005 mg/L.

Ammonia was detected in all tributaries with most annual mean concentrations comparable to those recorded during the previous five years, although West Boylston Brook showed a surprising increase.

TABLE 9

AMMONIA-NITROGEN CONCENTRATIONS (mg/L)

STATION	Muddy	French	Gates	Malagasco	Malden	Waushacum	W. Boylston	Stillwater	Quinapoxet
ave2014	0.067	0.034	0.014	0.015	0.009	0.025	0.049	0.012	0.017
ave2013	0.065	0.051	0.008	0.013	0.006	0.014	0.014	0.007	0.012
ave2012	0.069	0.045	0.007	0.014	0.011	0.019	0.013	0.008	0.012
ave2011	0.066	0.039	0.005	0.016	n/s	n/s	0.022	0.010	0.015
ave2010	0.061	0.120	<0.005	0.010	0.010	n/s	0.012	0.011	0.014
ave2009	0.077	0.068	0.005	0.018	0.017	n/s	0.015	0.015	0.015
ave2008	0.068	0.061	0.008	0.014	0.025	n/s	0.014	0.012	0.013
ave2007	0.079	0.112	0.009	0.015	0.024	n/s	0.039	0.017	0.016

Phosphorus is an important nutrient, and the limiting factor controlling algal productivity in Wachusett Reservoir. EPA Water Quality Criteria recommend a concentration of no more than 0.05 mg/L total phosphorus in tributary streams in order to prevent accelerated eutrophication of receiving water bodies. Concentrations measured in nine Wachusett tributaries during 2014 ranged from 0.012 mg/L to 0.121 mg/L total P, with annual mean concentrations from 0.018 mg/L to 0.037 mg/L (Table 10). All annual concentrations were comparable to the previous six years. Only six samples exceeded the recommended maximum concentration of 0.05 mg/L (compared to seventeen in 2012) and all were collected during or immediately following a storm event.

TABLE 10

TOTAL PHOSPHORUS CONCENTRATIONS (mg/L)

STATION	Muddy	French	Gates	Malagasco	Malden	Waushacum	W. Boylston	Stillwater	Quinapoxet
ave2014	0.019	0.031	0.025	0.034	0.025	0.025	0.037	0.018	0.020
ave2013	0.021	0.032	0.017	0.027	0.018	0.023	0.019	0.015	0.017
ave2012	0.027	0.049	0.025	0.044	0.028	0.029	0.035	0.023	0.027
ave2011	0.024	0.036	0.017	0.042	n/s	n/s	0.044	0.019	0.017
ave2010	0.015	0.055	0.013	0.026	0.019	n/s	0.016	0.016	0.017
ave2009	0.017	0.033	0.017	0.045	0.030	n/s	0.022	0.012	0.013
ave2008	0.013	0.038	0.020	0.055	0.027	n/s	0.035	0.016	0.024
ave2007	0.015	0.041	0.018	0.027	0.020	n/s	0.025	0.021	0.073

Total suspended solids are those particles suspended in a water sample retained by a filter of 2μm pore size. These particles can be naturally occurring or might be the result of human activities. Total suspended solids in Wachusett tributaries ranged from <5.0 mg/L to 66 mg/L, but only fourteen of 108 samples contained more than the detection limit. Total suspended solids are not considered a parameter of concern except during storm events when measurements in excess of 100 mg/L are not uncommon.

Total organic carbon (TOC) and UV-254 measure organic constituents in water, and are a useful way to predict precursors of harmful disinfection byproducts. TOC in the tributaries ranged from 1.12 to 25.5 mg/L, with an overall mean of 5.02 mg/L. The highest readings were again recorded from French and Malagasco Brooks, with the lowest from West Boylston, Muddy, and Gates Brooks. There were also some very low readings from Malagasco Brook in August, September, and October.

Measurements of UV-254 were comparable to TOC measurements. Organic compounds such as tannins and humic substances absorb UV radiation and there is a strong correlation between UV absorption and organic carbon content. The highest UV-254 readings were from Malagasco and French Brooks, and the lowest annual means were from West Boylston Brook and Gates Brook.

Nutrient loading estimates for nitrate-nitrogen, ammonia, total phosphorus, and total organic carbon in the Stillwater and Quinapoxet Rivers and in Gates Brook were calculated by multiplying daily flow (cu ft) by concentration (mg/L), multiplying by a unit conversion factor for daily load in kilograms, and then summing all daily totals to obtain an annual load (Table 11). Measured concentrations were used when available, and missing concentrations were filled using concentrations measured on the closest previous sampling date. Missing long term flows of a day or more were filled using USGS estimated daily flow. Gates Brook estimates are for January-July only as no flow information is available for the last five months of 2014. Nutrient loading estimates did not address short term changes in flow and concentration that occurred during storm events.

Nutrient loading estimates were also made for five tributaries with weekly flow monitoring (Table 11). Daily flow (cu ft) based on the most recent previous weekly measurement was multiplied by daily concentration (mg/L) and then by a unit conversion factor to give load in kilograms. Measured concentrations were used when available and missing data points were filled with concentrations from the closest previous sampling date. No loading estimates were made for Muddy Brook or Trout Brook due to a lack of reliable flow data, and estimates did not address short term changes in flow and concentration that took place during storm events.

Estimated loads for most tributaries and parameters in 2014 were comparable to estimates from the previous three years. Elevated estimated loads of nitrate-nitrogen, total phosphorus, and total organic carbon in Malden and Waushacum Brooks and of ammonia in Gates, Waushacum, and West Boylston Brooks are due to elevated flows rather than increased concentrations.

Samples were collected monthly for nitrite-nitrogen and total suspended solids, but most results were less than the detection limit and no useful loading information was developed.

TABLE 11

ANNUAL NUTRIENT LOADING (kg) – 2011-2014

	NO_3-N	NO_3-N	NH_3-N	NH_3-N	total P	total P	TOC	TOC
	2014	2011-13	2014	2011-13	2014	2011-13	2014	2011-13
French	829	283-987	155	91-177	81	67-139	19,410	13k-29k
Malagasco	330	497-1051	13	17-45	28	38-110	11,443	10k-28k
Malden	**1441**	1159-1270	31	21-42	**76**	61-74	**15,363**	8.7k-11k
Waushacum	**558**	303-429	**136**	51-128	**185**	130-152	**44,015**	25k-32k
W. Boylston	341	254-636	**17**	3-14	15	7.4-35	1272	542-1784
Gates	2217*	2159-4978	**48***	18-31	76*	63-100	6309*	6.6k-14k
Stillwater	6106	5948-13k	515	371-546	723	783-1587	191,387	127k-352k
Quinapoxet	13,236	7608-16k	884	436-1031	954	774-1681	233,331	126k-352k

*data available from January-July only

Stormwater sampling supplements routine monthly sampling and more accurately characterizes total annual loading. Elevated concentrations were noted during some storms, primarily in Gates Brook, and much of the annual loading appears to take place during large storm events, although this is due to increases in flow rather than an increase in pollutant concentrations in most cases. Stormwater sampling provides a much better measurement of total annual flow and consequently a more reliable estimate of nutrient loading. A more detailed discussion of stormwater data and nutrient loads is included in Section 3.6.

3.4 SPECIFIC CONDUCTANCE

Fresh water systems contain small amounts of mineral salts in solution. Specific conductance is a measure of the ability of water to carry an electric current, dependent on the concentration and availability of these ions. Elevated conductivity levels indicate contamination from stormwater or failing septic systems, or can be the result of watershed soil types.

Specific conductance was measured weekly at all nineteen tributary stations. Nearly three quarters of all measurements from Trout Brook were below 80 μmhos/cm; only three measurements from all other stations were as low. Values greater than 800 μmhos/cm were recorded in 79% of samples from the two stations on Gates Brook, and in almost half of samples from West Boylston Brook. The maximum recorded value (5021 μmhos/cm) was measured at Scarlett Brook during a mixed precipitation event in February.

Annual median specific conductance ranged from a low of 74.8 μmhos/cm (Trout Brook) to a high of 1,113 μmhos/cm (Gates Brook 4). Annual medians were comparable to previous years but were the highest in five years at seven of the sampling stations. It is likely that this was caused by natural variations in rainfall and stream flow and not the result of declining water quality.

3.5 TURBIDITY

Routine weekly samples were collected from all tributary stations throughout the year. Individual measurements ranged from 0.17 NTU to 29.5 NTU. Three samples with turbidity of 60 NTU or higher were collected from West Boylston Brook and Scarlett Brook during storm events in February but were directly related to road treatments and stormwater problems at the adjacent DPW yard. Annual median values ranged from 0.27 NTU in Cook Brook to 4.8 NTU in Muddy Brook. The overall watershed mean of 1.85 NTU (median of 0.82 NTU) was slightly higher than the previous four years.

Storm events continued to have a strong negative impact on turbidity, with a watershed median of 1.14 NTU for all storm samples but a median of only 0.75 NTU for dry weather samples.

3.6 STORMWATER SAMPLING

Stormwater sampling efforts continued during 2014 to help quantify the impacts from rain events, with sampling done approximately monthly during nine storm events from January through October. Samples were collected from Gates, Malagasco, and Waushacum Brooks and from the Quinapoxet River. Standardized sampling methodologies were used to collect time-based discrete samples during the rising limb of the storm hydrograph and then to develop flow-based composite samples that were transported for analysis to the MWRA Deer Island lab. The same methodology was used five times to obtain samples from Gates and Malagasco Brook during the falling limb of the storm, with a single grab sample collected to represent the falling limb in all other instances and from the other two stations. Samples for nitrate-nitrogen, nitrite-nitrogen, ammonia, total phosphorus, total organic carbon, and total suspended solids were collected by automatic samplers at three locations and by hand at Waushacum Brook.

Concentrations of nitrate-nitrogen, nitrite-nitrogen, and ammonia in samples from rising and falling limbs of selected storms were similar to or lower than concentration in samples collected monthly during dry weather, just as they were in 2012 and 2013. Total organic carbon concentrations were greater during storms in Gates Brook and the Quinapoxet River but no clear difference was noted in Malagasco or Waushacum Brooks. Concentrations of total phosphorus were higher during the rising limb in Malagasco and Gates Brooks and in the Quinapoxet River than concentrations in monthly samples. Concentrations of total suspended solids were 2-10 times greater in wet weather samples than in dry weather samples at all four sampling locations.

Annual nutrient loads estimates were improved using supplemental data from storm events. Nutrient loads were calculated by multiplying flow by concentration to give interval load and then multiplying by a unit conversion factor for total load in kilograms. When storm data were available, rising limb and falling limb concentrations were multiplied by measured storm flow.

Only a small percentage of storms were sampled during 2014 and inclusion of event data resulted in only a slight increase in overall annual flow in the four monitored tributaries. Measured flow during storm events was 2-10 times greater than flow estimated from weekly stage measurements. Annual nitrate-nitrogen, nitrite-nitrogen, and ammonia loads using storm event data were lower or similar to loads calculated with monthly data. Total organic carbon, total phosphorus, and total suspended solids loads also changed only slightly in three of the tributaries, but were much higher in Gates Brook.

TABLE 12

IMPACT OF STORM EVENTS ON ANNUAL NUTRIENT LOAD

			NH3-N	NO3-N	NO2-N	TOC	TP	TSS		flow
% change	Quinapoxet		-15.8	-11.5	0.1	4.9	2.5	6.2		0.1
% change	Malagasco		1.9	2.6	3.0	2.2	5.7	12.9		2.5
% change	Waushacum		-0.7	0.6	1.8	1.6	2.1	2.3		2.0
% change	Gates		1.4	-5.0	6.8	15.3	64.9	142.4		-1.3

3.7 SPECIAL STUDIES

Monitoring of potential short term and long term water quality impacts from forest management activities is underway. Monitoring of short term impacts consists of monthly sampling at active logging sites above and below stream crossings when flow is present or during storm events. All new sites were mapped using GPS during 2014. Five sites with eight stream crossings were visited to collect water quality samples and establish baseline conditions, although not all had flow during all occasions.

The long term monitoring project is designed to collect data at a control site and an active site for a ten year period before, during, and following completion of forestry operations. The study includes monthly dry weather discrete grab sampling and quarterly storm event monitoring using automatic samplers. Monthly sampling occurred when flow was present. Parameters monitored are flow, pH, temperature, dissolved oxygen, turbidity, total suspended solids, total organic carbon, ammonia, nitrate, nitrite, and total phosphorus.

Macroinvertebrate samples were collected at a number of reservoir tributaries during the spring of 2014 and are being sorted, identified, and counted. Additional macroinvertebrate sampling was done in 2012. Information obtained from 2012 and 2014 will be compared with historic long term macroinvertebrate data from the same locations and will be presented in a future water quality report.

High concentrations of bacteria remain an issue at Asnebumskit Brook (Princeton Street). Samples were sent to a microbial source tracking laboratory that used real-time polymerase chain reaction technology to identify dogs as the source. Staff will contact homeowners in the area and provide educational materials that should help to eliminate the problem.

4.0 RESULTS OF RESERVOIR MONITORING PROGRAM

4.1 FECAL COLIFORM

Bacterial transect samples were collected from twenty-three surface stations on the reservoir beginning in late April after ice melted. Samples were collected monthly, twice monthly, or weekly throughout the year to document the relationship between seasonal bacteria variations and visiting populations of gulls, ducks, geese, and other waterfowl. Data were also used to judge the effectiveness of bird harassment activities. Sample locations were shown previously on Figure 3 and all data are included in Table 13.

TABLE 13

FECAL COLIFORM TRANSECT DATA (colonies/mL)
Wachusett Reservoir - 2014

	4/25	5/21	6/18	7/25	8/27	9/10	9/24	10/9	10/27	11/3	11/10	11/21	11/25	12/4	12/12	12/18	12/22
Cosgrove	1	0	2	0	3	**15**	0	0	2	0	1	2	5	4	0	0	0
B-2	n/a	0	0	1	8	0	0	0	1	2	0	9	8	0	0	0	0
B-3	1	0	0	1	8	7	1	0	3	3	1	9	**11**	0	0	0	0
C-1	n/a	1	1	0	3	1	0	0	3	4	0	5	5	2	0	1	0
C-3	0	0	5	0	1	0	0	0	1	2	2	3	**14**	1	0	2	0
C-5	n/a	0	2	0	3	2	1	0	0	1	3	7	5	2	1	0	0
D-1	0	0	1	0	7	0	0	0	0	2	7	4	5	2	5	1	1
D-2	0	0	0	0	2	1	1	0	**31**	2	2	**13**	9	3	0	3	0
D-4	n/a	0	2	0	2	4	0	0	0	2	9	4	**14**	0	0	1	1
E-2	6	0	0	0	0	5	0	4	6	7	4	5	7	2	2	0	0
E-4	n/a	0	0	0	0	1	0	0	0	**16**	3	0	3	1	4	0	0
F-2	4	0	0	0	1	7	0	1	1	0	3	3	3	1	1	1	1
F-3	n/a	0	1	1	5	4	5	0	4	3	4	9	4	1	2	1	0
F-4	0	0	0	0	1	**10**	1	1	1	2	1	4	6	1	1	2	0
G-2	0	0	0	0	0	8	2	2	3	4	1	0	3	2	**13**	3	8
H-2	n/a	0	0	0	0	0	0	1	1	2	4	2	5	3	**17**	5	**11**
I-2	n/a	0	1	0	1	0	13	1	1	4	1	1	7	1	**15**	6	9
J-2	n/a	0	0	0	0	1	0	0	1	2	0	2	0	7	**14**	0	9
J-3	0	0	0	0	0	7	0	0	3	1	3	**10**	3	**16**	**24**	**34**	**117**
J-4	0	0	1	0	0	**27**	1	4	5	7	**13**	2	**12**	**28**	**28**	2	**19**
K-2	n/a	0	0	1	0	1	1	0	4	6	0	5	**19**	**15**	**23**	**14**	**18**
M-1	n/a	0	1	0	0	1	0	0	3	5	2	0	3	**11**	**22**	**18**	**38**
N-1	0	5	0	0	0	0	1	1	2	4	0	4	4	7	**19**	**20**	9

Lab accident on 4/25 responsible for missing data

The MWRA Southborough Lab switched from mFC broth to mFC agar during 2014. It is the same media type but in a different format. The analytic method for fecal coliform remains the same. MWRA staff did appropriate comparative testing and determined that there should be no statistical difference in results, and have been certified by the Massachusetts DEP for use of the agar.

Ice cover was present into April and most waterfowl had dispersed before open water was present in the spring. Fecal coliform concentrations generally remained low throughout the reservoir until late November, although slightly elevated concentrations were noted at assorted sample locations in September, October, and early November. The source of a high count in a sample collected adjacent to the intake in September remains unknown.

Higher concentrations were noted across the reservoir in late November after smaller water bodies began to freeze and large groups of roosting birds returned to the reservoir. Bird harassment activities were successful in moving birds south and away from the Cosgrove Intake, but elevated concentrations at sampling stations located at the south end of the reservoir remained common through the end of the year.

Fecal coliform samples were collected seven days per week by MWRA staff from the John J. Carroll Water Treatment Plant at Walnut Hill in Marlborough. EPA's fecal coliform criteria for drinking water require that a minimum of ninety percent of all source water samples contain less than 20 CFU/100mL. All 363 samples collected at Walnut Hill contained less than the standard, with a concentration of 10 CFU/100mL at the end of November the maximum reported for the year and most samples containing 0 CFU/100mL. The Division has put considerable time and effort into implementing a rigorous bird harassment program, and the results in 2014 again proved to be very effective.

4.2 WATER COLUMN CHARACTERISTICS

4.2.1 FIELD PROCEDURES

Division staff routinely record water column profiles in Wachusett Reservoir for the following hydrographic parameters: temperature, specific conductance, dissolved oxygen concentration, percent oxygen saturation, and hydrogen ion activity (pH). This involves use of a field instrument known as a multiprobe to record data starting at the surface and then recording repeated measurements as the instrument is gradually lowered to the bottom. Measurements are recorded at one meter intervals, except during periods of isothermy and mixing (generally November through March) when intervals of two or three meters are adequate to characterize the water column.

The multiprobe used by the Division to measure water column profiles is a "MiniSonde 5" paired with a "Surveyor 4" water quality logging and data display system manufactured by Hydrolab Corporation (now part of the Hach Company located in Loveland, Colorado). These instruments are routinely charged and calibrated during the field season. At the conclusion of field work, data recorded by the logging system is downloaded as an EXCEL spreadsheet.

In 2011, the multiprobe was upgraded to measure chlorophyll *a* with the addition of a fluorometer, and this has proved to be a valuable tool for detecting aggregations of phytoplankton at depth. Chlorophyll *a* is the most abundant photosynthetic pigment in algae composing the phytoplankton community and the amount of chlorophyll *a* measured in a sample serves as a surrogate for total phytoplankton biomass.

Preliminary calibrations of the fluorometer were conducted based on comparisons to chlorophyll *a* concentrations measured in duplicate samples submitted to MWRA laboratory staff at Deer Island. Refinement of the initial calibrations is ongoing. During *in situ* measurements the relative intensity of the fluorometry signal has been extremely useful in pinpointing the depths with the greatest density of phytoplankton, allowing them to be targeted for sampling.

4.2.2 THERMAL STRATIFICATION

Typical of most deep lakes and reservoirs in the temperate region, Wachusett Reservoir becomes thermally stratified in summer. The development of stratification structure usually begins in late April or early May when increasing solar radiation and atmospheric warming cause a progressive gain of heat in surficial waters. Stratification is most pronounced during summer when the water column is characterized by three distinct strata: a layer of warm, less dense water occupying the top of the water column ("epilimnion"), a middle stratum characterized by a thermal gradient or thermocline ("metalimnion"), and a stratum of cold, dense water at the bottom ("hypolimnion"). This thermal structure is weakened in fall as heat from the upper portion of the water column is lost to the increasingly cold atmosphere. In late October or early November, the last vestiges of stratification structure are dispersed by wind-driven turbulence and the entire water column is mixed and homogenized in an event known as fall "turnover."

Profile measurement during the period of thermal stratification is important for many reasons, including the following: (1) to monitor phytoplankton growth conditions and detect "blooms" of potential taste and odor causing organisms associated with discrete strata of the water column (see section on phytoplankton), (2) to track the progress of the Quabbin "interflow" through the Wachusett basin during periods of water transfer, and (3) to monitor water quality within each stratum and determine appropriate depths for vertically stratified nutrient sampling. During the stratification period, profiles are measured weekly at Basin North/Station 3417 in conjunction with plankton monitoring (see section 4.2.4).

4.2.3 THE QUABBIN "INTERFLOW" IN WACHUSETT RESERVOIR

The transfer of water from Quabbin to Wachusett Reservoir via the Quabbin Aqueduct has a profound influence on the water budget, profile characteristics, and hydrodynamics of Wachusett Reservoir. In a typical season, the amount of water transferred from Quabbin to Wachusett ranges from 50-100% of the volume of the Wachusett Reservoir. The period of peak transfer rates generally occurs from June through November. However, at any time of the year, approximately half of the water in the Wachusett basin is derived from Quabbin Reservoir.

The peak transfer period overlaps the period of thermal stratification in Wachusett and Quabbin Reservoirs. Water entering the Quabbin Aqueduct at Shaft 12 is withdrawn from depths of 13 to 23 meters in Quabbin Reservoir. These depths are within the hypolimnion of Quabbin Reservoir where water temperatures typically range from only 9 to 13° C from June through October. This deep withdrawal from Quabbin is colder and denser relative to epilimnetic waters in Wachusett Reservoir. However, due to a slight gain in heat from mixing as it passes through Quinapoxet Basin and Thomas Basin, the transfer water is not as cold and dense as the hypolimnion of Wachusett. Therefore, Quabbin water transferred during the period of thermal stratification flows conformably into the metalimnion of Wachusett where water temperatures and densities coincide.

The term 'interflow' describes this metalimnetic flow path for the Quabbin transfer that generally forms between depths of 6 to 16 meters in the Wachusett water column. Interflow water quality is distinctive from ambient Wachusett water in having a low specific conductivity characteristic of Quabbin Reservoir. Multiprobe measurements of conductivity readily distinguish the flow path of Quabbin water within Wachusett Reservoir. The interflow penetrates through the main basin of Wachusett Reservoir (from the Route 12 Bridge to Cosgrove Intake) in about 3 to 5 weeks depending on the timing and intensity of transfer from Quabbin. The interflow essentially connects Quabbin inflow to Cosgrove Intake in a "short circuit" with limited mixing with ambient Wachusett Reservoir water.

In 2014, the Quabbin transfer was continuously transferring water from late May through late October. A total volume of 47.3 billion gallons (178,912,104 cubic meters) was delivered to Wachusett via the Quabbin aqueduct during 2014; equivalent to 79% of the volume of Wachusett Reservoir. The total volume for the year was within the normal range over the past 10 years.

4.2.4 SEASONAL PATTERNS IN PROFILE MEASUREMENTS

Thermal stratification of the water column and the presence of the Quabbin interflow stratum are major determinants of vertical gradients and patterns recorded in profile measurements. Profiles depicting water column characteristics on June 23, August 28, October 14, and November 4 (Figures 4-7) show how hydrographic parameters change with depth from early in the stratification period through fall "turnover" when mixing homogenizes the entire basin volume and restores equilibrium conditions with the atmosphere.

General trends in water column temperature and dissolved oxygen concentrations during the stratification period can be discerned in these profiles. Specifically, temperatures change in the epilimnion and metalimnion, but temperatures in the hypolimnion remain between 8 and 10° C throughout the summer. Dissolved oxygen values remain near 100% saturation in the epilimnion most of the year due to this stratum being exposed to the atmosphere and mixing due to wind-induced turbulence. In contrast, saturation values in the metalimnion and hypolimnion decline progressively due to microbial decomposition processes and the isolation of these strata from the atmosphere. The supply of oxygen at depth cannot be replenished until thermal structure is dissipated and "turnover" occurs. However, dissolved oxygen in the hypolimnion remains sufficient (typically >4.5 mg/L), even through the fall, to provide suitable habitat for cold water salmonids that inhabit the reservoir.

Hydrogen ion activity (pH) in Wachusett Reservoir is determined ultimately by the exchange of inorganic carbon between the atmosphere and water (the carbon dioxide-bicarbonate-carbonate "buffering system"). Generally, pH values in Wachusett Reservoir are unremarkable, ranging from around neutral (pH=7) to slightly acidic (pH=6). Specific patterns of pH distribution vertically in the water column and seasonally over the year are mainly determined by the opposing processes of photosynthesis and respiration, but are not depicted in Figures 4 through 7 since this parameter typically exhibits only minor fluctuations.

Specific conductance ("conductivity") profiles in Wachusett Reservoir reflect the interplay between native water contributed from the Wachusett watershed and water transferred from Quabbin. The Quinapoxet and Stillwater Rivers are the two main tributaries to Wachusett Reservoir and are estimated to account for approximately 75 percent of annual inflow from the reservoir watershed. Measurements of conductivity in these rivers generally range between 60 and 240 uS/cm with an average value between 125 and 150 uS/cm. In contrast, the average conductivity value of Quabbin water is approximately 40 uS/cm.

During periods of isothermy and mixing (November through March), conductivity values throughout the main Wachusett basin typically range from 75 to 145 uS/cm depending on the amount of water received from Quabbin the previous year. During the summer stratification period the Quabbin interflow is conspicuous in profile measurements as a metalimnetic stratum of low conductivity.

Interflow penetration at Basin North/3417 was first observed on June 16, becoming established as a defined layer by June 23 (Figure 4) as revealed by the conductivity profile. This indentation in the conductivity profile intensifies (extends to lower conductivity values) over the period of transfer as water in the interior of the interflow undergoes less mixing with ambient reservoir water at the boundaries of the interflow stratum. The epilimnion occupied the top 5.5 meters of the water column on this date and had reached a temperature of 21.5° C. Epilimnetic dissolved oxygen measured 105% saturation on this date due to photosynthetic activity by phytoplankton. Visible on the June 23 profile is a peak in chlorophyll *a* concentration at a depth of 9 meters, directly in the middle of the Quabbin interflow strata. This is evidence that phytoplankton were aggregated at that depth, which subsequent sampling confirmed.

The interflow continued to become more fully established, remaining as a discrete layer through the summer months. On August 28, the "bulge" in the conductivity profile (Figure 5) shows the typical mid-summer configuration of the fully established interflow with a thickness of eight meters present between depths of 6 and 14 meters with conductivity reaching minimum values of around 75 uS/cm. The epilimnion still occupied the top six meters of the water column with a temperature of 23.5° C. The steep gradient in temperature and density between the epilimnion and interflow can be seen in this profile where the temperature decreases 7° C between depths of 5.5 and 6.5 meters. Also visible on this profile is a spike in chlorophyll *a* concentration at a depth of 10.5 meters, once again directly in the middle of the Quabbin interflow strata. This peak on the profile corresponded to the highest density of phytoplankton found in samples collected on that day.

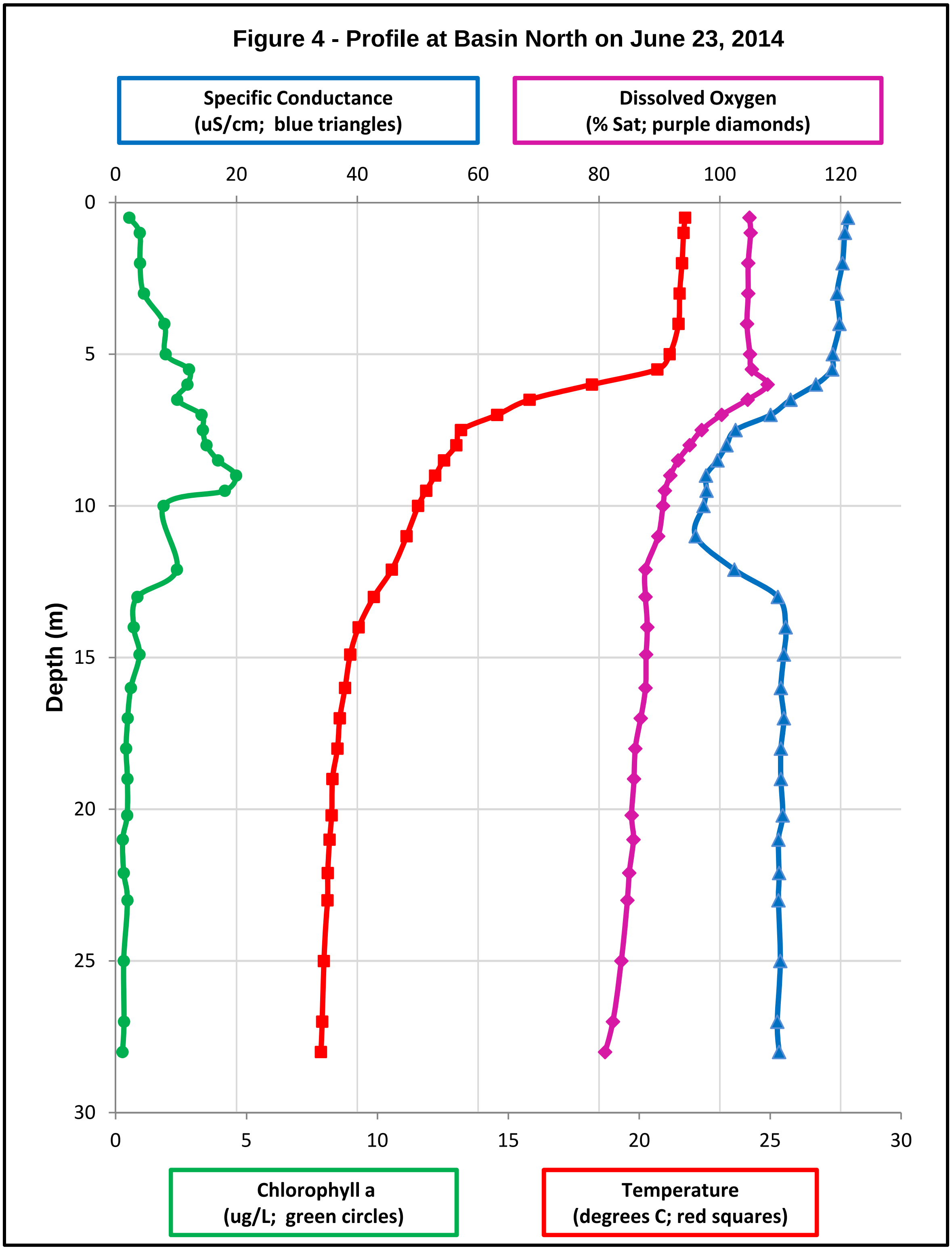


Figure 4 - Profile at Basin North on June 23, 2014
Specific Conductance
(uS/cm; blue triangles)
Dissolved Oxygen
(% Sat; purple diamonds)
0
20
40
60
80
100
120
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Chlorophyll a
(ug/L; green circles)
Temperature
(degrees C; red squares)

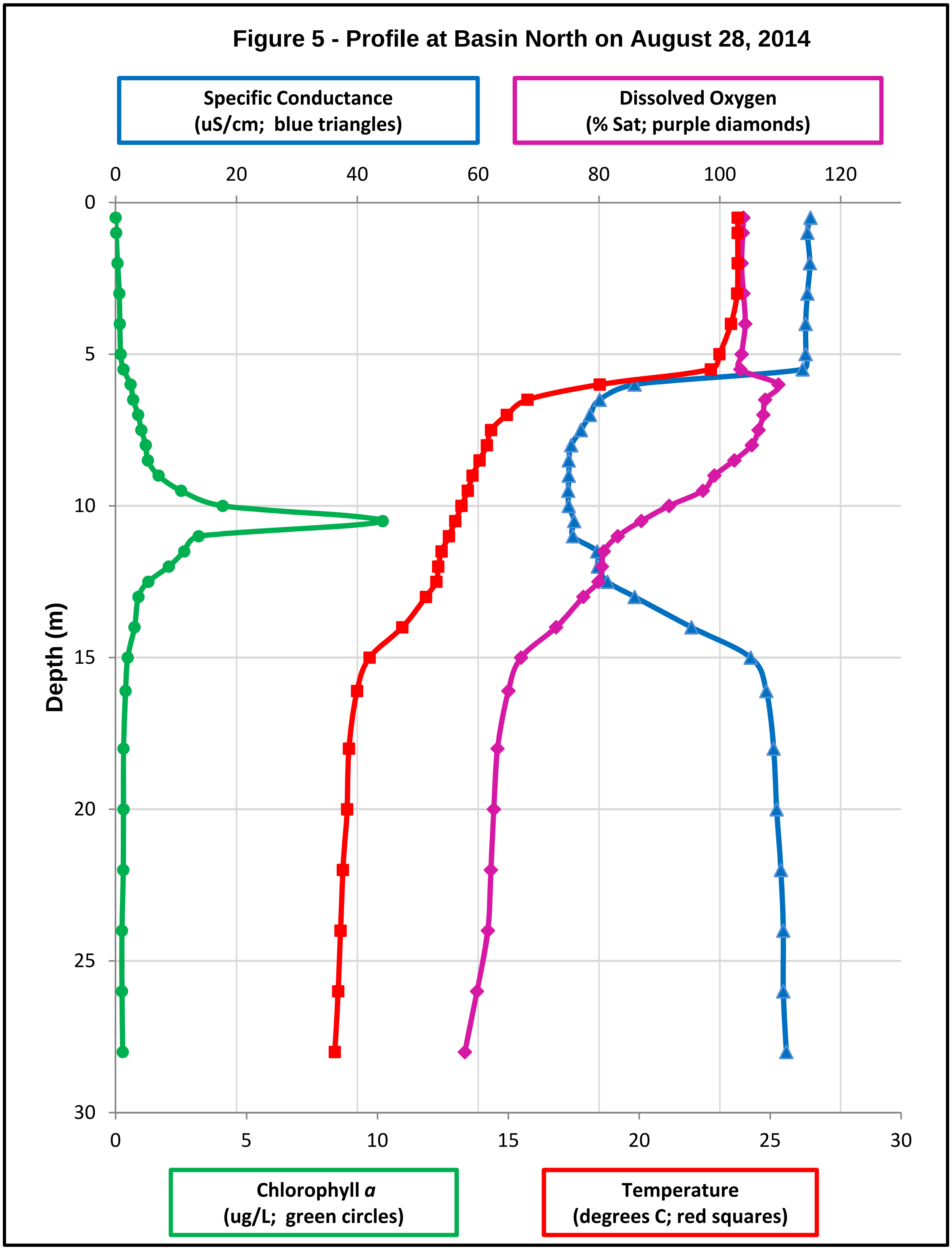


Figure 5 - Profile at Basin North on August 28, 2014
Specific Conductance
(uS/cm; blue triangles)
Dissolved Oxygen
(% Sat; purple diamonds)
0 20 40 60 80 100 120
Depth (m)
0 5 10 15 20 25 30
0 5 10 15 20 25 30
Chlorophyll *a*
(ug/L; green circles)
Temperature
(degrees C; red squares)

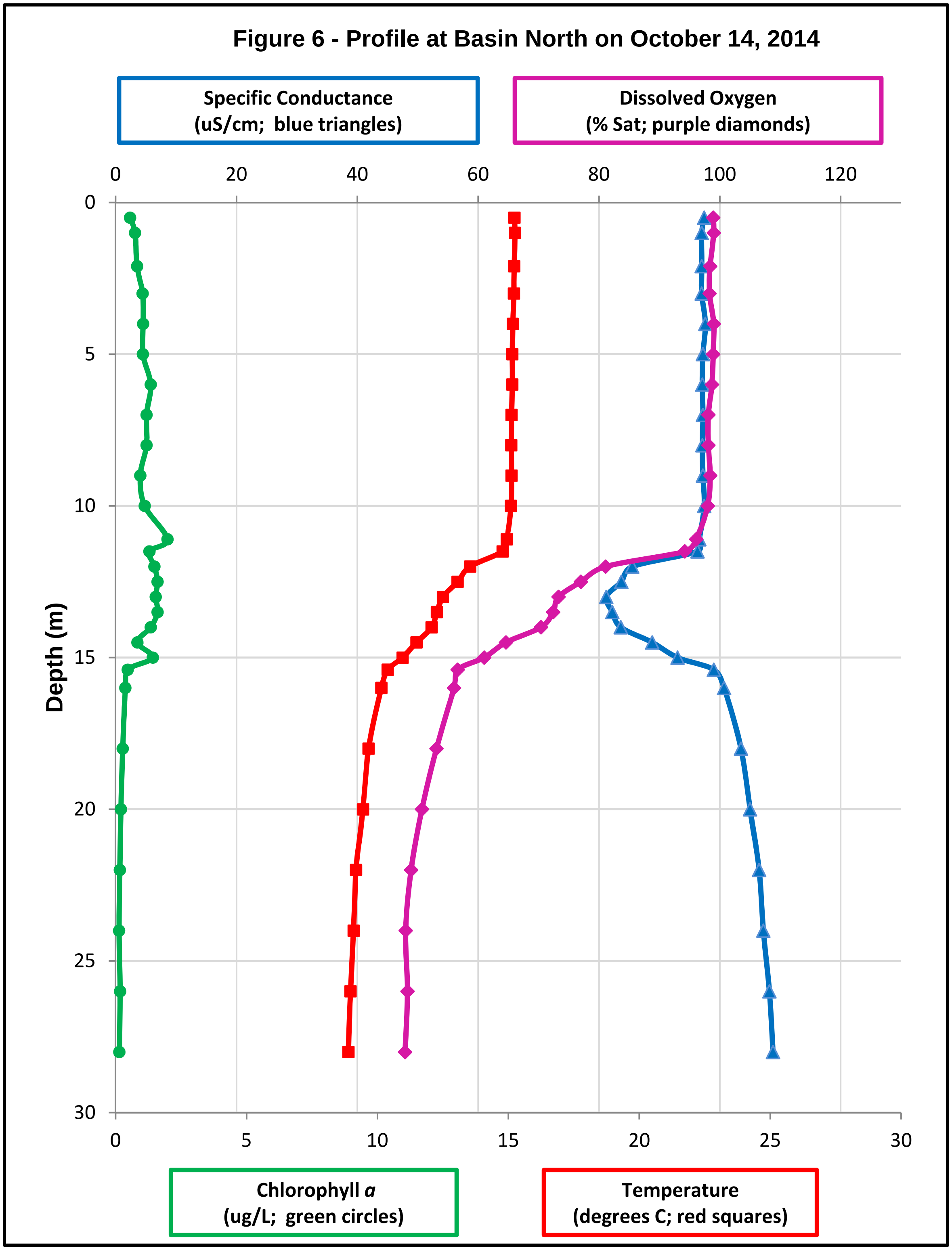


Figure 6 - Profile at Basin North on October 14, 2014
Specific Conductance
(uS/cm; blue triangles)
Dissolved Oxygen
(% Sat; purple diamonds)
0 20 40 60 80 100 120
Depth (m)
0 5 10 15 20 25 30
0 5 10 15 20 25 30
Chlorophyll *a*
(ug/L; green circles)
Temperature
(degrees C; red squares)

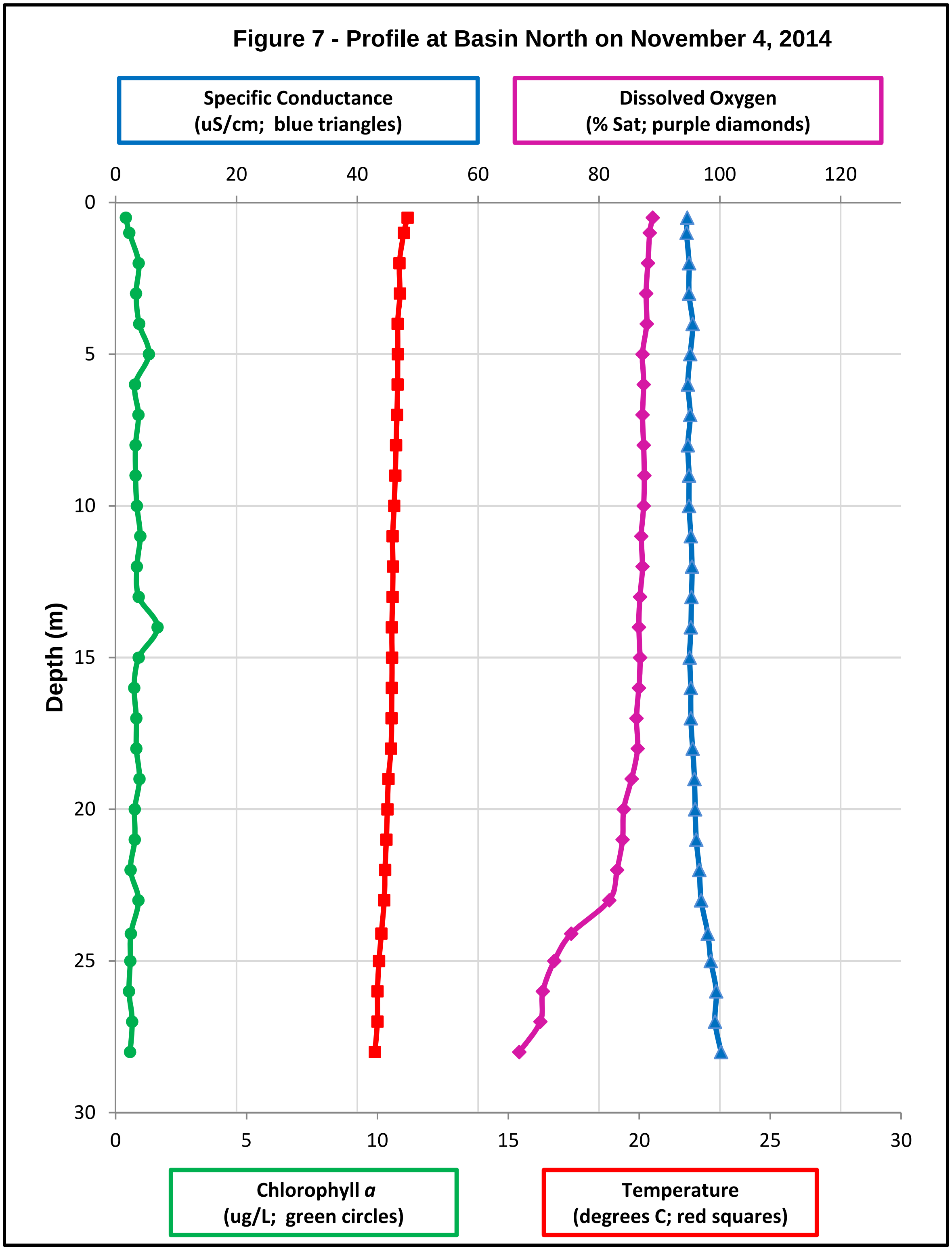


Figure 7 - Profile at Basin North on November 4, 2014
Specific Conductance
(uS/cm; blue triangles)
Dissolved Oxygen
(% Sat; purple diamonds)
0
20
40
60
80
100
120
Depth (m)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
Chlorophyll *a*
(ug/L; green circles)
Temperature
(degrees C; red squares)

The epilimnion started to steadily lose heat in mid-September. By October 14 (Figure 6), heat losses and wind energy had eroded the thermocline downward such that the epilimnion occupied the top 11.5 meters of the water column and the interflow stratum was partially homogenized within it. At this point, the interflow layer was reduced to a total thickness of only 3.5 meters, as evidenced by the lower specific conductivity values between 11.5 and 15 meters. Dissolved oxygen remained near saturation in the epilimnion, but had declined to between 48% and 57% saturation in the hypolimnion. Phytoplankton activity was minimal at this time and the chlorophyll *a* profile was comprised of low values throughout the water column.

Less than a month later, a profile recorded on November 4 (Figure 7) documents the breakdown of the stratification structure and reveals that turnover was imminent, though not yet completed. This profile shows the water column was nearly isothermal, with a difference of only 1° C from the surface to the bottom (9.9° C-11.1° C). Fall turnover exposes the entire basin volume to the atmosphere, thereby replenishing dissolved oxygen concentrations throughout the water column. The last vestiges of the hypolimnion are apparent in that dissolved oxygen within the bottom 5 meters of the profile had increased from the previous week but had still not completely mixed. Conductivity values were constant at approximately 95 uS/cm from the surface down to 23 meters; below that depth values were slightly higher and ranged from 98 to 100 uS/cm.

4.3 NUTRIENTS

4.3.1 FIELD PROCEDURES

Nutrient dynamics in Wachusett Reservoir were documented through a program of quarterly sampling as follows: at the onset of thermal stratification (May), in the middle of the stratification period (July), near the end of the stratification period (October), and during a winter period of mixis before ice cover (December). Samples were collected at three main monitoring stations consisting of Basin North/Station 3417, Basin South/Station 3412, and Thomas Basin (see Figure 2).

Grab samples were collected in the epilimnion, metalimnion, and hypolimnion during the period of thermal stratification and near the top, middle, and bottom of the water column during mixis. Water column profiles of temperature, dissolved oxygen, and other parameters measured with a multiprobe were evaluated in the field to determine depths for metalimnetic samples.

Quarterly sampling continued to be performed in collaboration with MWRA staff at the Deer Island Central Laboratory who provided sample containers and were responsible for all sample analysis. Sampling protocol, chain-of-custody documentation, and sample delivery were similar to those established during the 1998-99 year of study. Details of sampling protocol are provided in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics (Worden and Pistrang, 2003).

Modifications to the quarterly sampling program have consisted only of a lower minimum detection limit for total Kjeldahl-nitrogen (reduced to 0.05 mg/L from previous limits of 0.2 and 0.6 mg/L) and the addition of UV254 absorbance (in 2000) to the suite of parameters being measured. Measurement of UV absorbance at a wavelength of approximately 254 nanometers serves as a relative assay of the concentrations of organic compounds dissolved in the water.

4.3.2 RESULTS OF NUTRIENT ANALYSES

The nutrient database for Wachusett Reservoir established in the 1998-99 year of monthly sampling and subsequent quarterly sampling through 2013 is used as a basis for interpreting data generated in 2014. The results from quarterly nutrient sampling in 2014 document concentrations were all within historical ranges, with the exception of a single measurement. At the Basin North station on July 23, the Total Phosphorous result collected at depth from the hypolimnion measured 0.019 mg/L, which was just outside the historical range and slightly higher than the previous high of 0.017 mg/L recorded at this station in May of 2005. Overall, however, nutrient concentrations for 2014 range from near average to below average (see Table 14 on the following page and the complete 2014 reservoir nutrient results in Appendix A). The Quabbin transfer from the end of May through October influenced the generally low nutrient results observed in the October and December samples.

The patterns of nutrient distribution in 2014 quarterly samples correspond closely to those documented in the comprehensive report on Wachusett Reservoir nutrient and plankton dynamics (Worden and Pistrang, 2003). These patterns consist most importantly of the following: (1) prominent seasonal and vertical variations with low epilimnetic concentrations in summer resulting from phytoplankton uptake, and conversely, higher concentrations accumulating in the hypolimnion due to microbial decomposition of sedimenting organic matter, (2) interannual fluctuations in nutrient concentrations and parameter intensities occurring across the system as a result of the divergent influences of the Quabbin transfer and the Wachusett watershed with temporary lateral gradients becoming pronounced for nitrate, silica, UV254, and conductivity, either increasing or decreasing downgradient of Thomas Basin depending on the dominant influence.

Reference Cited:

Worden, David and Larry Pistrang. 2003. Nutrient and Plankton Dynamics in Wachusett Reservoir: Results of the MDC/DWM's 1998-2002 Monitoring Program, a Review of Plankton Data from Cosgrove Intake, and an Evaluation of Historical Records. Metropolitan District Commission, Division of Watershed Management.

Table 14 - Wachusett Reservoir Nutrient Concentrations:
Comparison of Ranges from 1998-2013 Database[1] to Results from 2014 Quarterly Sampling [2]

Sampling Station[3]	Ammonia (NH_3; ug/L)		Nitrate (NO_3; ug/L)		Silica (SIO_2; mg/L)		Total Phosphorus(ug/L)		UV254 (Absorbance/cm)	
	1998-2013	Quarterly14	1998-2013	Quarterly14	1998-2013	Quarterly14	1998-2013	Quarterly14	2000-2013	Quarterly14
Basin North/3417 (E)	<5 - 16	5	<5 - 176	5 - 64	0.59 - 4.62	1.11 - 2.45	<5 - 17	6 - 15	0.032 - 0.089	0.039 - 0.057
Basin North/3417 (M)	<5 - 51	5-14	<5 - 180	23 - 66	0.77 - 4.67	2.01 - 2.59	<5 - 20	5 - 8	0.032 - 0.102	0.042 - 0.060
Basin North/3417 (H)	<5 - 41	5-38	48 - 225	33 - 124	1.27 - 5.06	2.09 - 3.87	<5 - 17	5 - 19	0.032 - 0.084	0.042 - 0.060
Basin South/3412 (E)	<5 - 15	5	<5 - 176	5 - 68	0.56 - 4.58	1.20 - 2.73	<5 - 20	5 - 15	0.031 - 0.101	0.039 - 0.067
Basin South/3412 (M)	<5 - 39	5	11 - 184	6 - 65	0.95 - 4.80	1.83 - 2.52	<5 - 22	5 - 18	0.032 - 0.128	0.037 - 0.061
Basin South/3412 (H)	<5 - 44	5-36	49 - 224	35 - 113	1.64 - 4.78	2.22 - 3.27	<5 - 37	6 - 11	0.036 - 0.111	0.046 - 0.069
Thomas Basin (E)	<5 - 18	5	<5 - 201	5 - 82	0.62 - 7.44	1.26 - 4.03	<5 - 27	5 - 16	0.026 - 0.305	0.038 - 0.165
Thomas Basin (M)	<5 - 27	5	<5 - 213	5 - 82	0.88 - 7.36	1.31 - 4.22	<5 - 29	5 - 17	0.026 - 0.334	0.039 - 0.162
Thomas Basin (H)	<5 - 57	5	<5 - 236	5 - 87	0.92 - 7.39	2.75 - 4.40	<5 - 29	5 - 13	0.027 - 0.345	0.032 - 0.165

Notes: (1) 1998-2012 database composed of 1998-99 year of monthly sampling and subsequent quarterly sampling through December 2013, except for measurement of UV254 initiated in 2000 quarterly sampling
(2) 2014 quarterly sampling conducted May, July, October, and December
(3) Water column locations are as follow: E = epilimnion/surface, M = metalimnion/middle, H = hypolimnion/bottom

4.4 PLANKTON

4.4.1 FIELD PROCEDURES

Plankton monitoring consists of three tasks conducted from a boat: measurement of water column "profiles" (see previous section), measurement of Secchi transparency, and grab sampling. This work is generally conducted at Basin North/Station 3417 during the late-April through early-November thermal stratification period. Basin North/Station 3417 is representative of the deepest portion of the basin and is outside the area adjacent to Cosgrove Intake where copper sulfate is applied on the infrequent occasions when "taste and odor" organisms attain problematic densities. The catwalk behind Cosgrove Intake is an additional location suitable for plankton grab sampling (Secchi and profiles are not recorded at this location). Seiche effects or turbulence from water withdrawals can destabilize stratification boundaries and obscure associated phytoplankton distribution patterns at Cosgrove Intake during summer. However, samples collected from the catwalk during the late-November through early-April period of mixis are adequately representative of the main basin, and samples collected under stratified conditions may not be representative of any other location but are informative as to plankton densities present right at the intake.

Monitoring frequency is generally weekly in early spring, fall, and winter increasing to twice a week (usually Monday and Thursday) during the period from May through September when episodes of rapid population growth ("blooms") by taste and odor organisms have occurred in the past. During the annual stratification period samples are typically collected near the middle of the epilimnion at a depth of three meters as well as at or near the interface between the epilimnion and metalimnion (typically at a depth of six or seven meters). Additional samples are often collected where profile measurements reveal elevated chloophyll *a* values. Additionally, surface samples are collected in June to monitor for increased densities of the cyanophyte *Anabaena,* which may accumulate at the surface. During the period of mixis, collection of samples at two depths (3 and 6 meters) generally suffices but other samples are collected as needed. Samples are collected using a Van Dorn Bottle and kept in a cooler until they are returned to the laboratory for concentration and microscopic analysis.

Measurement of water column "profiles" entails the use of a Hydrolab minisonde MS5 multiprobe to record hydrographic parameters such as temperature, dissolved oxygen, hydrogen ion activity (pH), specific conductance, and chlorophyll *a* (see Section 4.2.1). These parameters are measured at one meter intervals as the multiprobe is lowered from the surface to record a profile of the entire water column. Secchi transparency is recorded as an approximate measure of the amount of particulates, mostly plankton, suspended in the water column.

During the stratification period, sampling is focused where profile measurements show a spike in dissolved oxygen concentration and/or a spike in chlorophyll *a* concentration. These are indicative of photosynthetic activity associated with a phytoplankton bloom or aggregation within a specific stratum of the water column. Additional grab samples are collected at the precise depth where spikes are indicated. Motile colonial Chrysophytes such as *Chrysosphaerella*, *Dinobryon* and Synurophytes such as *Synura* are known to produce subsurface blooms in Wachusett Reservoir and are the most potent taste and odor taxa generally encountered. The aggregation stratum that these organisms have historically preferred is often between 6 and 8 meters, coincident with the steep temperature gradient at the interface between the epilimnion and the metalimnetic interflow (see Section 4.2.2). However, in recent years chlorophyll *a* maxima have been documented at depth, with associated high levels of these organisms found inhabiting the middle or even lower portion of the interflow layer.

MWRA and DCR have analyzed the historical phytoplankton dataset and identified two incremental values for each taste and odor taxa that warrant additional monitoring or action. The first value is an early monitoring trigger. If baseline monitoring reveals a density greater than the early monitoring trigger level, monitoring frequency is increased to provide additional information about the density of those taxa and changes over time. The second value is a treatment consideration trigger. If monitoring reveals a density of taste and odor taxa greater than the treatment consideration trigger level, this triggers a discussion about whether or not a treatment should be considered.

4.4.2 CONCENTRATION AND MICROSCOPIC ANALYSIS OF PHYTOPLANKTON

Prompt acquisition and distribution of information on phytoplankton densities is critical for agency decisions on the need for additional sampling or algaecide applications to avoid taste and odor problems. The method of sand filtration for concentration of phytoplankton samples has long been in use by the Division because it enables relatively rapid analysis of samples while subjecting organisms to minimal damage or distortion. The specific method used is documented in Standard Methods Twelfth Edition (1965, pages 669-671). The method entails gravity filtration of sample water through a layer of fine sand. The concentrated sample and sand is gently washed with waste filtrate water in a beaker to detach organisms from the sand grains, and promptly decanted after the sand has been allowed to settle. A known quantity of the concentrated sample is then analyzed microscopically using quantitative techniques.

Phytoplankton taxa in concentrated samples are enumerated using a Sedgewick-Rafter (S-R) Cell which enables phytoplankton densities to be quantified. Each concentrated sample is mixed to homogenize the sample and then 1 ml of the sample is withdrawn with a pipette and placed into the S-R Cell. Initial inspection of phytoplankton within the S-R Cell is accomplished with a stereozoom microscope capable of magnification from 7X to 45X. Use of this instrument to scan the entire S-R Cell is important to detect colonies of certain motile taxa present at low densities such as *Synura*, colonies floating against the underside of the cover such as *Anabaena,* or to view large colonies such as *Uroglenopsis*. Analysis of surface samples collected in June is limited to scanning unless *Anabaena* is detected at densities sufficient to warrant enumerating using a compound microscope (see below).

Scanning of the entire S-R Cell enables colonial “taste and odor” organisms to be identified and quantified at very low densities. Colonies observed in the S-R Cell using the stereozoom microscope are quantified by counting the number of colonies and then measuring their average diameter using a compound microscope (see below). This information, along with the known concentration factor arising from sand filtration, is used to calculate and express densities of colonial “taste and odor” organisms as Areal Standard Units (see below).

After the scanning procedure described above, microscopic analysis of phytoplankton samples is next performed with a compound microscope at a magnification of 200X using either bright field or phase-contrast illumination. Approximately 15 minutes are allowed for the phytoplankton to settle to the bottom of the S-R Cell before enumeration. Phytoplankton is enumerated in a total of ten fields described by an ocular micrometer. The area of the ocular field is determined by calibration with a stage micrometer and the fields are selected for viewing at approximately 0.5 cm intervals across the length of the S-R Cell. If the initial count of ten fields reveals that known taste and odor organisms are present in densities approaching or surpassing the early monitoring or action trigger thresholds, up to forty additional fields are recorded for the density of that particular organism in order to increase the accuracy of the count.

Phytoplankton densities are expressed as Areal Standard Units (ASUs; equivalent to 400 square microns) per milliliter. The area of each specimen viewed in each counting field is estimated using the ocular micrometer (the ocular field is divided into a ten by ten grid, each square in the grid having a known area at 200X magnification). In the case of taxa which form gelatinous envelopes or are enclosed in colonial mucilage, such as *Microcystis*, the area of the envelope is included in the estimate for that specimen. The areal extent of certain colonial taxa, such as the diatoms *Asterionella* and *Tabellaria*, is estimated by measuring the dimensions of one cell and multiplying by the number of cells in the colony. Cell fragments or structures lacking protoplasm, such as lorica of *Dinobryon*, diatom frustules, and thecae of dinoflagellates, are not included..

During the peak season, phytoplankton sample splits are sent weekly to the MWRA lab in Southborough for automated plankton analysis with a Fluid Imaging FlowCAM system. This system is calibrated to recognize and enumerate five taste and odor taxa of interest. Split sample FlowCAM results are useful in comparing results to total densities for taste and odor taxa calculated by Division biologists using sand filtration and microscopic analysis.

4.4.3 PHYTOPLANKTON MONITORING RESULTS

Phytoplankton monitoring in 2014 revealed high overall densities of greater than 1,000 ASU/mL as soon as the reservoir was ice free and the sampling program resumed. Prominent spring diatom blooms of *Asterionella* and *Cyclotella* in April and May are common features of the reservoir's annual succession of plankton, and 2014 proved no different. However, in 2014 the Chrysophyte *Uroglenopsis* attained high densities in mid-May concurrent with the elevated diatom counts, resulting in atypically high algae counts that peaked at 2,373 ASU/mL in the 3m sample on May 22nd. Historically, high spring diatom levels have not had any negative drinking water quality impacts. Despite the additional high levels of *Uroglenopsis* being present at the same time, no taste and odor issues were experienced this spring. Although the 2014 pattern of high spring *Uroglenopsis* has not been observed since 2005, it is noteworthy that *Uroglenopsis* was a prominent component of the reservoir phytoplankton from 1993-2002. Peak *Uroglenopsis* densities have typically been observed during cool water conditions in the early spring or fall periods, with measurable densities lasting a period of 4-5 weeks.

Diatoms remained the dominant group in reservoir samples until June 22nd. *Dinobryon* levels increased slowly over time to this point, while *Synura*, a taxa that has been documented to cause taste and odor issues even at low densities, was observed to proliferate quickly at depth from observed levels of 21 ASU/mL on June 9th and 27 ASU/mL on June 16th to 74 ASU/mL on June 23rd. This resulted in the treatment of the typical prescribed area in the North Basin with Copper Sulfate the following day on June 24th. The treatment appeared to have the desired effect, as *Synura* levels recorded in samples collected by MWRA at Cosgrove Intake on June 25th measured less than 2 ASU/mL at all depths recorded. Frequent montitoring of *Synura* levels at Basin North (located outside of any treatment area) indicates that densities were elevated for approximately two more weeks after the rapid increase, with *Synura* recorded as 0 ASU/mL on July 7th.

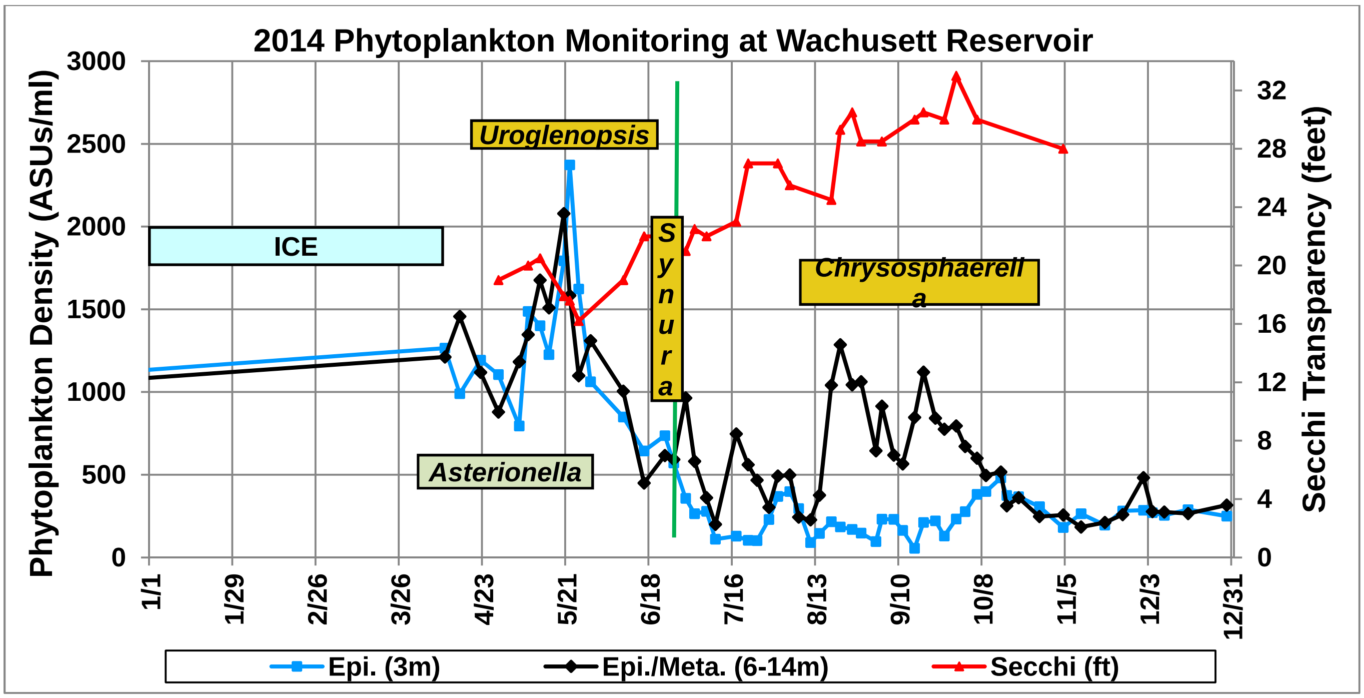
Chrysophytes and Synurophytes have recently been the most frequent nuisance algae in Wachusett Reservoir. In addition, periods of high density have been documented to last for a more prolonged period of time than in the past. At least one consideration is that with better technology and the capability to monitor chlorophyll *a* levels *in situ* in real time, biologists are better able to locate, sample, and identify aggregations of algae. This could make an event “appear” to last longer as compared to sampling efforts conducted prior to 2011, when sampling efforts were not guided by *in situ* chlorophyll *a* probe. Without the in situ chlorophyll *a* probe, aggregation layers than can change depths from day to day are likely to be missed. For example, elevated levels of *Synura* and *Chrysosphaerella* documented in 2014 were located at depth within the metalimnetic interflow, were dynamic and did not remain at a constant depth, and produced no traceable dissolved oxygen peak. Without a chlorophyll *a* probe it simply would not be possible to track the movements of these motile organisms.

After the *Synura* peak, overall phytoplankton densities continued a steady decline until early August, when Chrysophyte densities increased at depth. Although *Chrysosphaerella* was not observed until July 28th, this organism reached high densities in fall of 2014, was present for nearly 4 months, and lasted much later into the season than is normally observed. *Chrysosphaerella* densities rose quickly and peaked at 749 ASU/mL at a depth of 9 meters on August 18th. Densities then declined slightly, until resurging at depth a month later in mid September. *Chrysosphaerella* densities did not dip below 100 ASU/mL until mid October and colonies were still present in measurable densities until the beginning of November. Fortunately, the high reported densities were generally constricted to a narrow aggregation stratum of water and did not result in any taste and odor issues. Presumably, the breakdown of the stratification layers at the Cosgrove Intake assists in dispersing organisms across a wider range of depths, thus lessening the impact of organisms populating a narrow range of depths.

Dinobryon was observed to be present in many samples from April through October. Although densities were most often quite low, it was by far the dominant *Chrysophyte* present in the month of June. Densities reached significant levels in mid June, increasing to a fleeting maximum of 548 ASU/mL on June 30th before quickly dissipating in July.

Anabaena made its usual seasonal appearance and persisted at low densities for most of the season, with low densities typically below 5 ASU/ml recorded sporadically from May through November. Only a single value above 10 ASU/mL was recorded all season, with 31 ASU/mL being reported for the June 16th sample.

FIGURE 8.



Green line is for algae treatment on 6/24/14 for *Synura*

Secchi transparency was good, increasing as the year went on to a maximum transparency of 33 feet recorded at the end of September. Lower spring transparencies were limited by the high densities of *Uroglenopsis* and *Asterionella*.

4.4.4 WACHUSETT RESERVOIR PHYTOPLANKTON IMAGES

Images shown on the following pages are examples of phytoplankton observed in Wachusett Reservoir during the past year.

FIGURE 9

Bacillarophyceae **(diatoms):** ***Tabellaria*****, September 11th 2014, Cosgrove Intake**

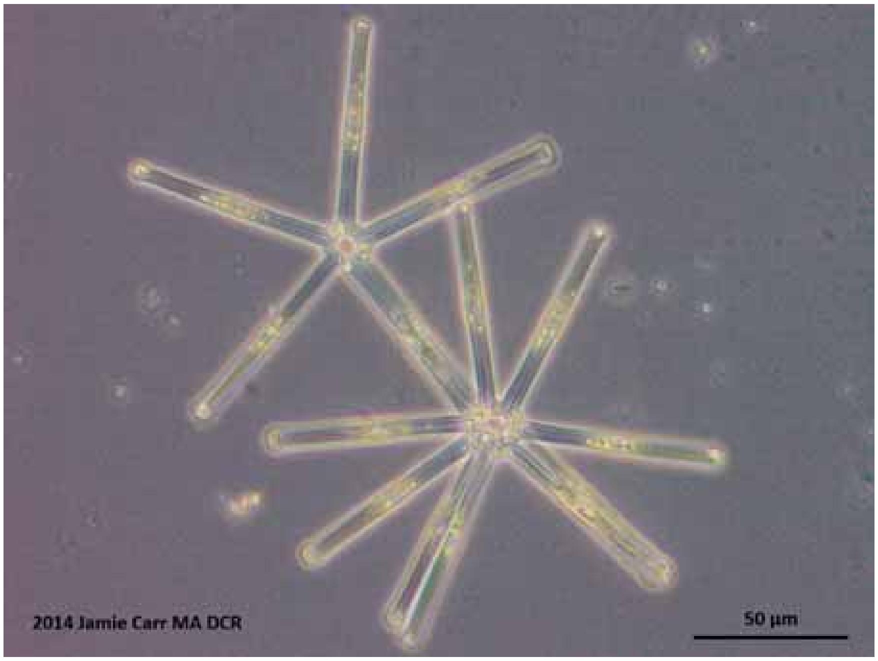


FIGURE 10

Chlorophyta **(green algae):** ***Draparnaldia*****, January 2nd 2015, collected along shoreline**

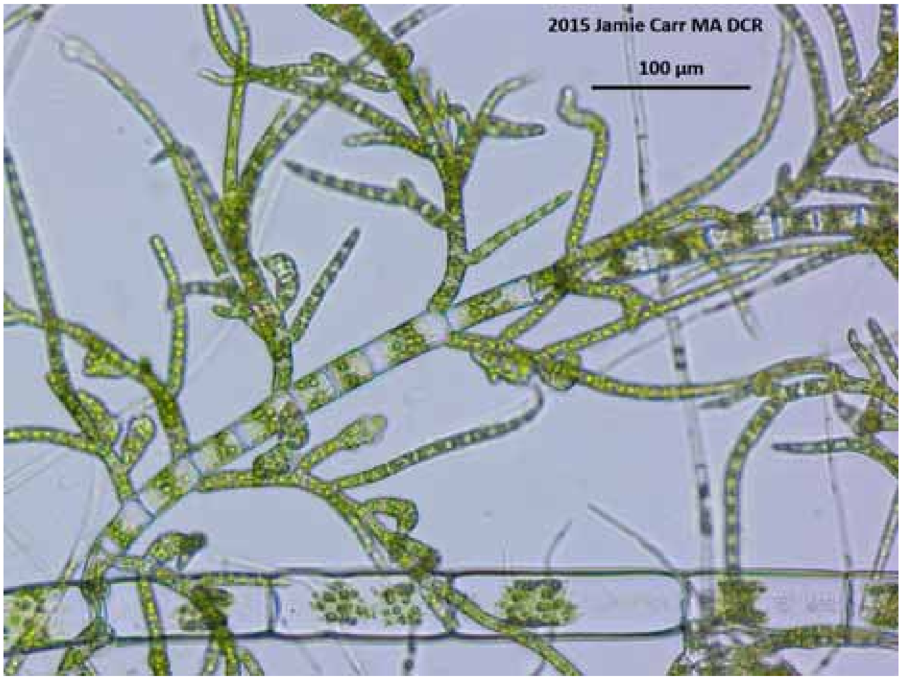


FIGURE 11

***Chrysophyta* (golden/golden-brown algae): *Dinobryon*, August 29th 2014, Basin North**

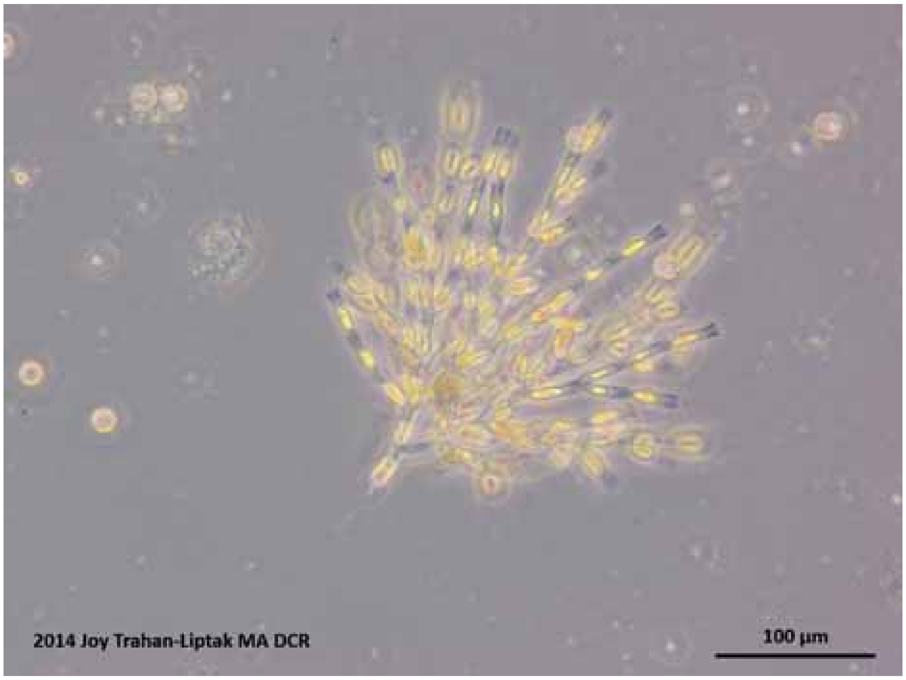


FIGURE 12

***Chrysophyta* (golden/golden-brown algae): *Chrysosphaerella*, August 14th 2014, Cosgrove Intake**

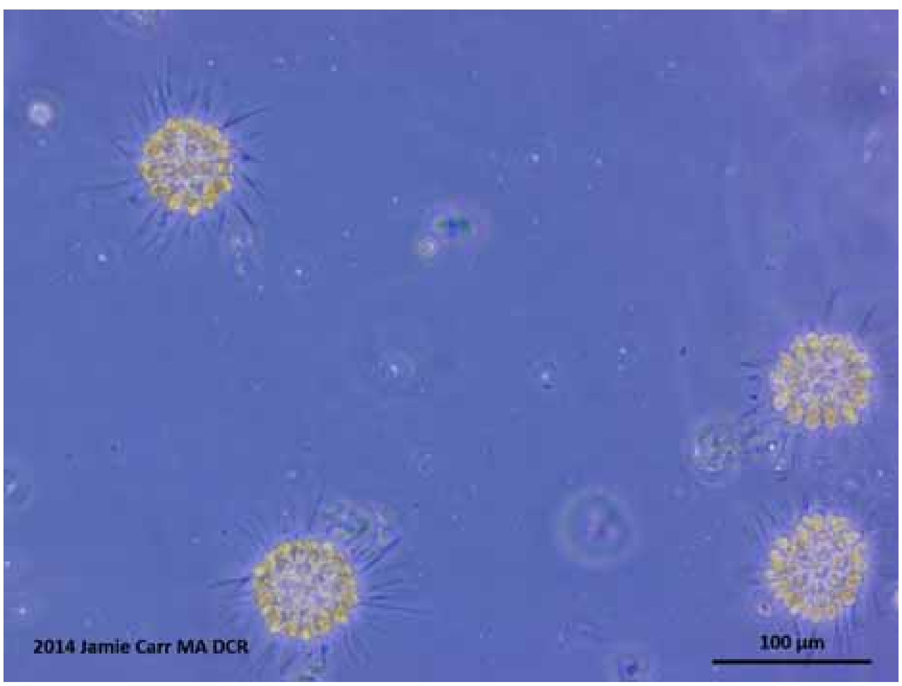
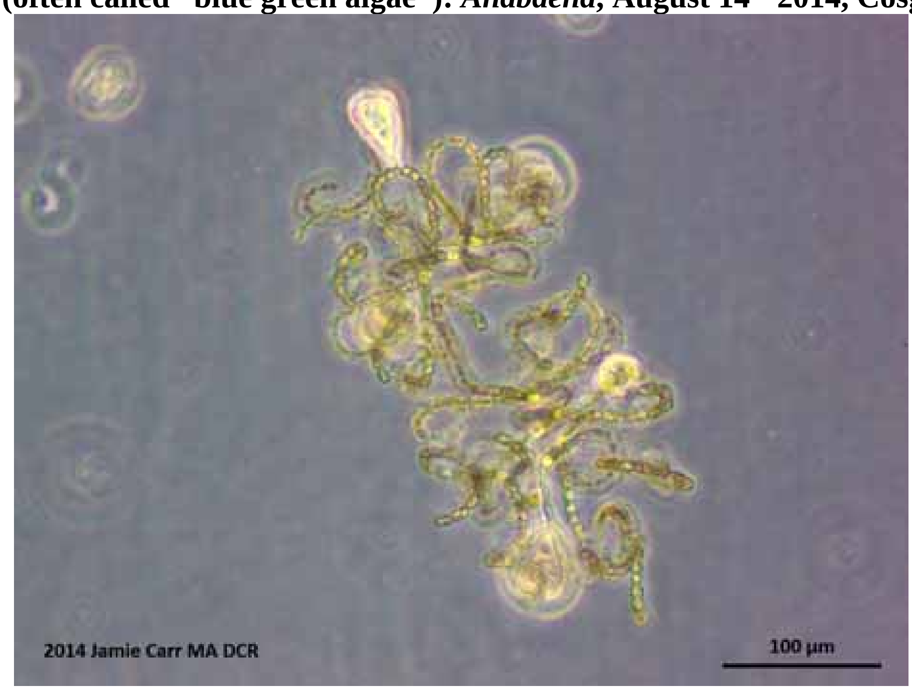


FIGURE 13

***Chrysophyta* (golden/golden-brown algae): *Uroglenopsis*, May 5th 2014, Cosgrove Intake**

FIGURE 14

***Cyanophyta* (often called "blue green algae"): *Anabaena*, August 14th 2014, Cosgrove Intake**

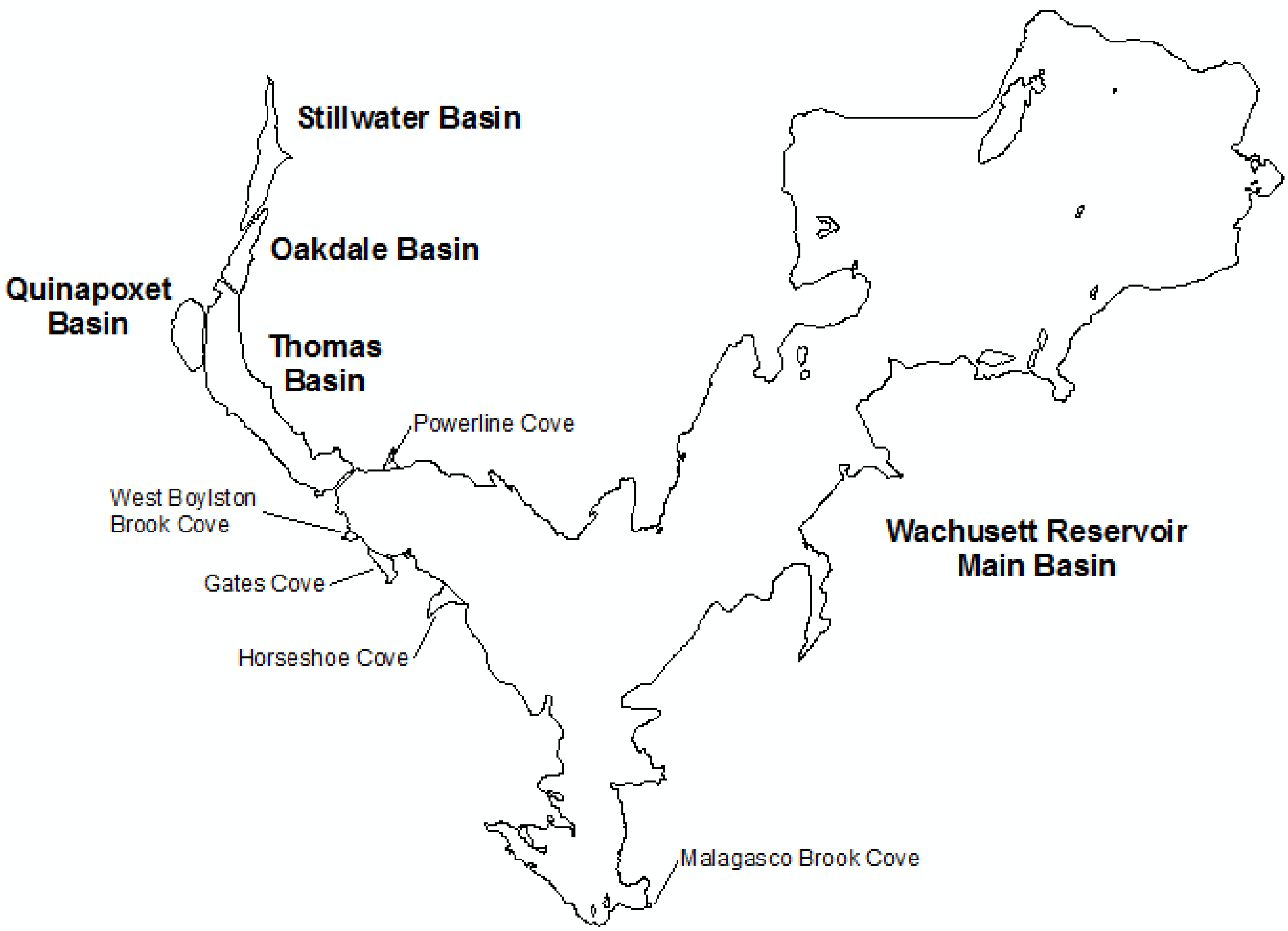


4.5 MACROPHYTES

4.5.1 THE THREAT OF INVASIVE AQUATIC MACROPHYTES

In August of 2001, a pioneering colony of Eurasian watermilfoil (*Myriophyllum spicatum;* referred to subsequently as "EWM") was observed for the first time in Oakdale Basin, a small basin in the upper reaches of the reservoir system (Figure 15). EWM is a non-native, invasive species of macrophyte known to aggressively displace native vegetation and grow to nuisance densities with associated impairments to water quality. Prior to 2001, this plant was restricted to the uppermost component of the reservoir system, Stillwater Basin, where its distribution has been monitored since 1999.

FIGURE 15



The expansion of EWM into Oakdale Basin represented a significant increase in the risk of a potentially rapid and overwhelming dispersal of this plant into the main reservoir basin. The water quality implications of such an event are serious and include increases in water color, turbidity, phytoplankton growth, and trihalomethane (THM) precursors. These increases result from the function of this plant and macrophytes in general as nutrient "pumps," extracting nutrients from sediment and releasing them to the water column, mostly as dissolved and particulate organic matter.

Fanwort (*Cabomba caroliniana*) is another non-native invasive plant that was first discovered as only sporadic individual plants present at the northern end of Stillwater Basin in 1999. Fanwort began to spread into Oakdale Basin in 2004. The spread of fanwort was initially more gradual than that of EWM, but in 2009 it surpassed EWM in total plants before decreasing in the past few seasons. Fragmentation is the most important mode of reproduction and dispersal of these species. Vegetative fragments are generally released at the end of the growing season when the plants undergo senescence. These fragments float for some time before sinking to the bottom and can take root and become established in suitable habitat. Control measures targeting both EWM and fanwort are discussed in the sections that follow.

4.5.2 WACHUSETT RESERVOIR INVASIVE MACROPHYTE CONTROL PROGRAM

The 2001 expansion of EWM into Oakdale Basin prompted the Division and the MWRA to design and implement an invasive macrophyte control program. This program was initiated in 2002 and continues to the present. The main components of this program have been the following: deployment of floating fragment barriers, maintenance of benthic barriers, annual hand-harvesting and DASH (Diver Assisted Suction Harvesting) plant removal efforts, and routine scouting throughout the reservoir system by the Division to ensure early detection of pioneering infestations (details of control efforts in previous years are provided in their annual reports). Harvesting efforts initially focused on Oakdale Basin, but both EWM and fanwort have gradually spread throughout Thomas Basin, located directly downstream, so this basin is also targeted in annual removal efforts. DASH was first utilized in 2012 and has been continued as an additional control strategy for dense patches of plant growth as a complement to the typical hand-harvesting efforts.

The annual preliminary spring aquatic plant GPS survey of Oakdale Basin was conducted on June 10th by Jamie Carr, DCR Aquatic Biologist and Matthew Salem, Aquatic Control Technology (ACT) staff. The survey revealed that spring aquatic vegetation was dominated by naiad (*Najas* sp.). Common occurrences of variable watermilfoil (*Myriophyllum heterophyllum*) and bladderwort (*Utricularia* sp.) were observed with scattered observations of coontail (*Ceratophyllum demersum*) and pondweeds (*Potamogeton robinnsii* and *Potamogeton pusilis*). Growth of Eurasian milfoil (*Myriophyllum spicatum*) and fanwort (*Cabomba caroliniana*) was present at several data point locations as single plant specimens and growth was similar to previous spring surveys (ACT 2014).

The first removal effort in 2014 began on July 8th and extended through to July 24th. This entailed four days with the DASH crew and eight days for traditional diver crews removing plants in Oakdale Basin, Thomas Basin, Powerline Cove, and Gates Cove. A total of approximately 10,508 EWM plants and 770 fanwort plants were removed. Additionally, the DASH crew spent 1.5 days working in Hastings Cove to remove approximately 1,974 variable millfoil plants from that location.

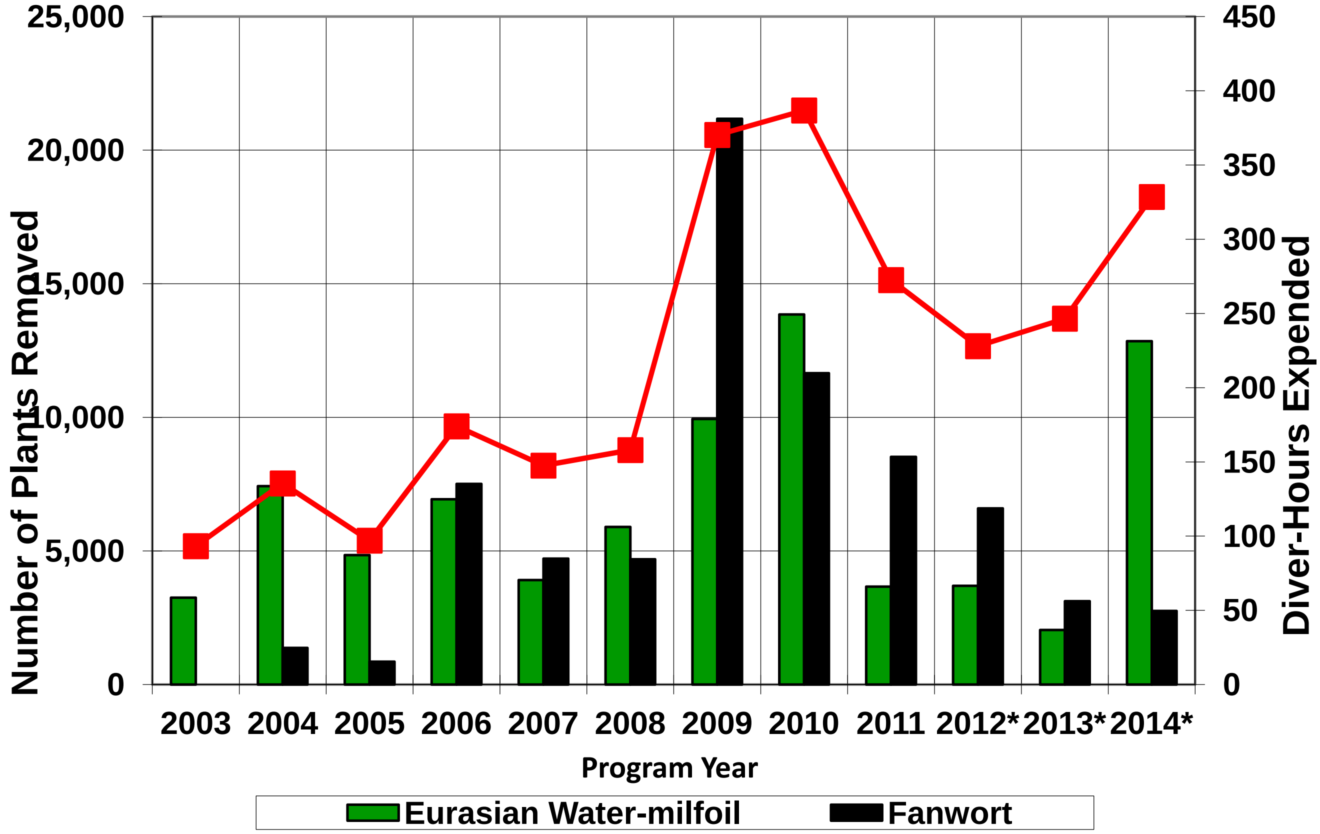
The second effort began on September 2nd and consisted of four days of DASH work and six days of diver hand-harvesting, which ended on September 12th. The initial phase of the second hand-harvesting effort was guided by Division observations of target plant re-growth. Scouting by ACT's Field Technician guided the remainder of the work, which focused on Oakdale and Thomas Basins, but also included work in Powerline Cove, Gates Cove, and West Boylston Brook Cove. A total of 2,341 EWM plants and 1,988 fanwort plants were pulled during the second effort.

The total number of EWM plants removed in 2014 was 12,849, the total number of fanwort plants removed was 2,758, and the total diver-hours expended were 383.5. The 2014 fanwort totals represent a slight decrease from 2013 harvesting totals, continuing a trend of 5 consecutive years of decreasing fanwort harvest totals (Figure 14). However, 2014 saw a marked increase in the number of EWM plants harvested; breaking a string of three consecutive years of decreased growth and returning the infestation to a density last observed in 2010. Reasons for the increase are not clear, but the majority of plants were harvested in the initial July effort, indicating that the EWM plants were already growing well at the beginning of July. The majority (62%) of all EWM plants harvested in 2014 were harvested in Oakdale Basin. Environmental factors such as water chemistry and temperature may play a role in providing favorable growth conditions for EWM. Additionally, new mapping technology and high resolution bathymetric maps resulted in the discovery and removal of several new stands of EWM plants.

The annual post-harvesting fall aquatic plant GPS survey of Oakdale Basin was conducted on October 3rd by DCR Aquatic Biologists Jamie Carr and Joy Trahan-Liptak as well as Matthew Salem from ACT. This survey documented an overall increase in non-target plant cover and biomass, with naiad and variable watermilfoil remaining the dominant species. A few specimens of EWM were observed along the shoreline, but no fanwort was observed.

In 2013, a localized but dense growth of variable watermilfoil in the Hastings Cove area of the main basin was harvested for the first time. Although there are other large but more sparse occurrences of variable watermilfoil in the main basin, the Hastings Cove infestation represents a discrete, dense source of potential plant fragments and is readily addressed by the plant removal techniques utilized in the main project area. In 2014, only 1,974 variable millfoil plants were removed from Hastings Cove; a marked decrease from the 18,376 plants removed from an area of only 1/3 of an acre in 2013. The time spent on this area also decreased, as the DASH crew spent 96 hours in Hastings Cove in 2013 and 24 hours in 2014 (ACT 2014).

Figure 16
Harvesting of Invasive Macrophytes: 2003 - 2014



- *2012-2014 totals include hand harvesting by divers as well as DASH
- In 2002 496.5 diver-hours were expended in removing an estimated 75,000 to 100,000 EWM plants

In addition to the activities summarized above, Division staff maintained floating fragment barriers at strategic "bottleneck" locations to restrict the movement of invasive fragments into down gradient portions of the reservoir system. These locations consist of the railroad trestle bridge between Stillwater Basin and Oakdale Basin and the Beaman Street Bridge between Oakdale Basin and Thomas Basin. The floating fragment barriers were initially purchased and deployed at these locations in 2002. Based on monitoring of fragments captured in the booms in 2013, the booms were re-configured for the 2014 season. Additionally, a 400 foot floating boom was deployed in a chevron configuration downstream of the Beaman Street Bridge and left in place for the entire 2013 and 2014 seasons. This boom is positioned at an angle to the shore and to the flow moving under the bridge, such that plant fragments are guided to the shoreline by the boom instead of continuing into Thomas Basin along with the current. Collection of fragments in the chevron boom was monitored closely in 2013 and 2014 to determine if fragments were bypassing the two upstream barriers. Evidence suggests that the chevron boom works well to trap invasive plant fragments. The Oakdale trestle boom appeared to function very well to prevent fragments from moving out of Stillwater Basin, while the Beaman Street boom will likely be reconfigured again for 2015 to improve its effectiveness.

Despite the line of fragment barriers, some invasive plant fragments are still reaching the main basin of the reservoir. Historically, evidence of this is represented by the occurrence of a small number of plants found in Powerline Cove. This cove is located immediately east of the Route 12 Bridge/Causeway on the northern shoreline of the main basin where power lines span the reservoir. Varying numbers of EWM and fanwort have been detected and removed from this cove over the past 12 years (Table 15). The high annual variation in EWM numbers in Powerline Cove may be related to the overall environmental factors driving growth in the larger basins as well.

TABLE 15

Summary of Harvesting Results in Powerline Cove

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
EWM	14	0	0	21	18	1	0	59	22	75	103	7	37
Fanwort	0	0	0	0	0	1	0	17	7	4	5	0	1

Invasive plants are now being found in other coves of the main basin of the reservoir. During shoreline scouting on August 29, 2011 EWM was found for the first time in Horseshoe Cove, located along the southern shore approximately one mile from both the Route 12 Causeway and Powerline Cove. These specimens were removed by DCR staff, but additional specimens were again detected in 2012. Also in 2012, EWM was detected for the first time in West Boylston Brook Cove (Table 16). This cove is located directly southwest of Powerline Cove on the opposite shoreline. These specimens were also removed by DCR staff and the area was later checked by ACT divers. EWM was found for the first time in Gates Cove in 2013, where 60 specimens found growing as small, individual plants were identified and removed. Unfortunately, this number increased in 2014, as the soft substrates found in Gates Cove provide ideal growth conditions for aquatic plants. Finally, a single EWM specimen was observed and removed from Malagasco Brook Cove on August 14, 2014. The location where the plant was found is behind a sediment containment curtain, seemingly ruling out the possibility of water transport to that location from within the reservoir. The small watershed makes an upstream source unlikely as well, meaning that it is likely that this single plant arrived via another vector such as a bird or human.

TABLE 16

Summary of EWM Removals in Coves of the Main Basin

	2010	2011	2012	2013	2014
Horseshoe Cove	0	4	6	0	0
W. Boylston Brook Cove	0	0	13	1	14
Gates Cove	0	0	0	60	141
Malagasco Brook Cove	0	0	0	0	1

The established populations of EWM and fanwort in the uppermost basin of the reservoir, Stillwater Basin, provide propagule pressure and an endless supply of potential plant fragments waiting to move downstream. Surveys in the main basin and the invasive plants found each year in the coves indicate that fragments are reaching and colonizing the main basin. With this in mind, a project was undertaken to begin removal of EWM and fanwort from the Stillwater Basin in 2013.

A contract was procured to begin a DASH plant removal project in the 34 acre Stillwater Basin on May of 2013. Variable watermilfoil, EWM and fanwort growth covered a significant portion of the basin; in many areas these plants were topped out and plant cover reached 100%. A first pass was performed in an attempt to remove as much of the biomass from as much of the basin as possible with multiple DASH boats working simultaneously to harvest invasive plants. A total of 333 cubic yards of dewatered plant biomass was removed over the course of the six month project in 2013. This project was continued in 2014, with a contractor working with multiple DASH units in the basin from May 12th to November 21st, and removed 209 cubic yards of plants. The reduced biomass harvested in 2014 is encouraging, as was the fact that making two complete attempts at harvesting the entire basin was more feasible to complete within a single season in 2014. It is anticipated that this will be a long term project with ongoing annual maintenance to reduce the biomass of invasive plants in this basin to a more manageable level.

Reference Cited:

Aquatic Control Technology. 2014. Wachusett Reservoir- Aquatic Invasive Macrophyte Control Program, 2014 Project Completion Report. Prepared for Massachusetts Water Resources Authority.

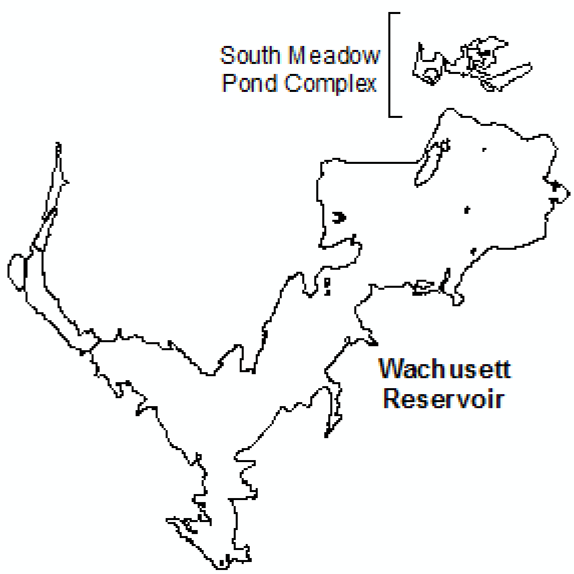
4.5.3 SUPPLEMENTAL INVASIVE MACROPHYTE CONTROL ACTIVITIES

Additional activities were conducted in 2014 in conjunction with the main components of the invasive control program. Details of these activities are presented below.

In August of 1996, at the invitation of Ed Brank of the MDC, Dr. Rick McVoy of MA DEP conducted an aquatic plant survey of the Wachusett Reservoir. This survey of the coves and upper basins of the reservoir served as one of the first documented surveys of the reservoir plant community and provides evidence for the absence of invasive Eurasian milfoil and fanwort that are believed to have arrived a few years later. Given Dr. McVoy's impending retirement in the fall of 2014, a unique opportunity presented itself to invite him back to recreate the 1996 survey of 18 years prior. DCR Aquatic Biologists Jamie Carr and Joy Trahan-Liptak joined Dr. McVoy in observing and recording aquatic plants at each of the locations surveyed in 1996. Anecdotal comparisons of the number, density, and type of plants observed in 2014 as compared to 1996 suggest that there has been a general increase in aquatic plants in many coves of the reservoir. General comments from Dr. McVoy based on his recollections were as follows: 1.) The fact that we were listing emergent species in the 1996 survey meant we were groping for any aquatic plants and we were not seeing any submerged species and 2.) It seems that the aquatic plant community in most of these coves has changed quite a bit, with more submerged aquatic plant density and diversity.

In August of 2010, the invasive macrophyte hydrilla (*Hydrilla verticillata*) was discovered in South Meadow Pond in the Town of Clinton. The South Meadow Pond complex is located only about 1,970 feet (600 m) north of Wachusett Reservoir, thus this infestation is at the "doorstep" of the reservoir.

FIGURE 17



Even though the South Meadow Pond complex is outside the Wachusett watershed, the close proximity of the hydrilla infestation to Wachusett Reservoir and the possible potential for transfer to the reservoir by waterfowl or bait buckets necessitates special management and monitoring efforts.

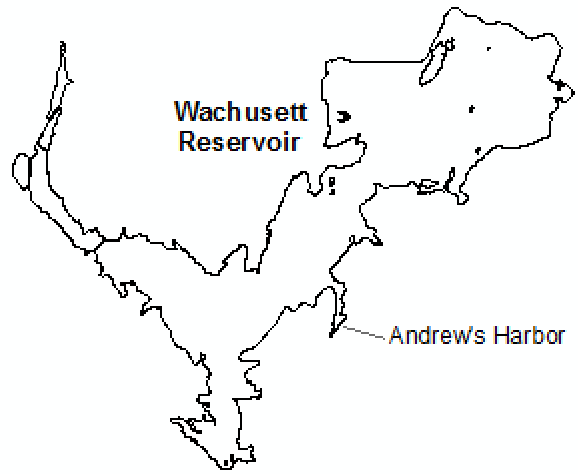
Within a month of the discovery of hydrilla in the South Meadow Pond complex, DCR and the MWRA collaborated on response efforts and implemented a program to suppress hydrilla biomass, hiring the contractor Aquatic Control Technology (ACT) to implement a control plan and apply herbicides. ACT's treatment and monitoring plan went into full swing in 2011, and has continued successfully in 2012, 2013, and 2014. Control of hydrilla has been impressive as only scattered individual plants are now present. More importantly, pre-management hydrilla tuber densities of 27.9 tubers/m^2 in 2010 have been incrementally reduced each year. The spring 2014 survey revealed a tuber density of only 0.35 tubers/m^2, while the fall 2014 survey did not find any tubers within the sampled locations. It is important to note that this result does not mean that there are no viable tubers present in South Meadow Pond, but rather that the density has been reduced to the point that collection is difficult with this sampling protocol. Control of the tuber bank is the key to the long term control of this invasive plant, and management results to this point have been very positive.

DCR Aquatic Biologists are continually scouting for known aquatic invasive plants in new locations, while at the same time keeping a lookout for any potential new introductions. In 2014, three new non-native aquatic plants were detected. It is important to keep in mind that not every non-native plants is necessarily invasive (i.e., cause harm to the environment, economy, human health, etc.). At this time it is difficult to determine precisely the invasive potential of each of these plants, although it appears unlikely that any of these three will require active management.

Mudmat (*Glossostigma cleistanthum*) was discovered in 2014 by ESS group consultants and DCR Aquatic Biologists. Initial surveys indicate that this diminutive plant appears to be well established in Wachusett Reservoir. A memorandum was created to detail what is documented in the literature, map the current distribution, and discuss the invasive potential of mudmat. The mudmat memorandum is included within this document as Appendix B.

DCR Aquatic Biologists observed and collected several waterwort plants in Andrews Harbor in August 2014 during a Wachusett Reservoir plant survey. These small plants are very difficult to identify to the species level and thus it was arranged for samples to be sent to Hamid Razifard to perform DNA analysis. Mr. Razifard is a Ph.D. student at the Les Lab at the University of Connecticut who specializes in the identification of waterwort plants. Mr. Razifard's tests produced the surprising result that our samples were a DNA match with Asian waterwort (*Elatine ambigua*). The current documented distribution of this plant in North America is limited to a handful of locations in the vicinity of Sacramento, California. It is possible, and quite likely, that this plant is much more widespread. However, given the small size of the plant, its variable morphology, and the difficulty with identification in the absence of DNA analysis, it seems likely that it has mostly been overlooked or misidentified. This plant does not appear to be a nuisance plant within its native range or in other regions where it has been introduced. However, it has been documented in three locations in the Wachusett Reservoir in 2014 and it will be further researched and monitored closely in 2015.

FIGURE 18



Onerow yellowcress (*Rorippa microphyla*), is listed by the Connecticut Agricultural Experiment Station as "banned, potentially invasive." Plant samples which key out to onerow yellowcress have been found in the Stillwater River upstream of Stillwater Basin by DCR Aquatic Biologists. Images of the plant with seed pods present were sent to Greg Bugbee at the Connecticut Agricultural Experiment Station, who confirmed the identification. This species appears to grow within cold, flowing waters, and similar plants which may be the same species have been observed within the Quinapoxet, Ware, and Quabbin Reservoir watersheds by DCR Aquatic Biologists. Though it may be locally dense, to this point this plant has not been observed to dominate native vegetation in any area. The distribution and potential impact of this plant will be monitored going forward.

Reference Cited:

Aquatic Control Technology. 2014. South Meadow Pond Complex 2014 Hydrilla Management Program Year End Report. Prepared for Massachusetts Department of Conservation and Recreation.

4.5.4 PLANS FOR INVASIVE PLANT CONTROL EFFORTS IN 2015

The invasive nature of EWM and fanwort necessitate a long-term commitment to annual control efforts in the upper reaches of the Wachusett Reservoir system if their dispersal into the main basin is to be prevented. To meet this challenge, DCR and the MWRA continue to work collaboratively to sustain annual control efforts and refine the control program as necessary.

Next year, during the 2015 growing season, plans call for a resumption of intensive DASH and hand-harvesting in Oakdale and Thomas Basins. The 3 year contract for this project has been updated to allow for finer scale mapping and tracking of where plants are being harvested, so that more information can be derived from year to year results. As usual, initial surveys will be conducted in May or June followed by harvesting in areas observed to support regrowth of invasive macrophytes. Dive crews will conduct additional hand-harvesting efforts during the summer as needed to suppress regrowth that occurs subsequent to initial harvesting efforts. The large scale Stillwater Basin DASH project is scheduled to resume again at the beginning of May 2015 for another full season of intensive harvesting.

Associated with hand-harvesting efforts, DCR Aquatic Biologists will continue systematic scouting for invasive macrophytes throughout the reservoir system to identify and target any pioneering specimens found in new locations. An updated bathymetric map of the reservoir has been developed and divided into sections to ensure complete coverage and help focus scouting efforts on those areas most susceptible to colonization by hydrilla and other invasive aquatic plants. New plants discovered in 2014 will be monitored to determine if spread is occurring and to evaluate if any potential management actions are prudent. The increase of Eurasian Water-milfoil in Gates Brook Cove is a concern and this area will be a focus for plant removal again in 2015. Additional actions to reduce the prime habitat currently available for invasive plants within this cove, such as dredging, are being considered.

Finally, DCR staff will continue to maintain floating fragment barriers at their strategic “bottleneck” locations as done in previous years. Changes to the boom configuration at the Oakdale Basin Railroad Trestle in 2014 appeared to be effective and will be maintained; the configuration of the boom under the Beaman Street Bridge will be revised for the 2015 season.
The chevron boom below Beaman Street will once again be deployed for the entirety of the growing/harvesting season to trap fragments and measure the effectiveness of the upstream booms.

5.0 SAMPLING PLAN FOR 2015

An expanded sampling program during the past decade has gathered ample background data and addressed a number of issues that had been identified in previous water quality summaries and Environmental Quality Assessment reports. Sampling locations were reduced in 2011 to include only direct tributaries to the reservoir and stations deemed historically significant or potentially threatened. Sampling frequency at six stations of lesser importance or with historically stable water quality was reduced further in 2014, with samples collected from these locations every other week instead of weekly. The Wachusett watershed sampling program for 2015 follows protocols used during 2014. Temperature, specific conductance, *E. coli*, and turbidity will again be measured weekly or biweekly at nineteen stations on eighteen tributaries during dry and wet weather. Additional sampling will be done as needed during 2015 if water quality conditions change and problems are noted, and to help locate occasional sources of contamination. Samples will also be collected to support any potential enforcement actions required by other Division staff. Nutrient samples will be collected monthly from nine tributary stations with available flow data and weekly UV-254 will continue to be collected from the Stillwater and Quinapoxet Rivers.

The routine sampling program provides data on the effects of storm events on tributary water quality using detailed precipitation data from several stations within or near the watershed. Sampling at Trout Brook to collect specific information on stormwater quality will be done approximately monthly as weather permits and once budgetary conditions improve. Additional stormwater sampling at several other locations will be done to obtain data on specific storm types (length, intensity, and season).

Understanding watershed hydrology is a necessary part of any water quality monitoring program. A continuation of the expanded hydrology monitoring program is planned for 2015. Precipitation data from NOAA weather stations in Worcester and Fitchburg, from the USGS stations on the Stillwater River in Sterling and the Quinapoxet River in Holden, and from a DCR rain gage in West Boylston will be collected daily. Snow pack measurements and calculation of snow-water equivalent amounts will be done regularly during the winter months throughout the watershed.

Depth will be recorded at seven stations and flow calculated using rating curves developed by Division Environmental Quality staff. Flow measurements will be taken throughout the year to correct or improve existing rating curves. Daily flow in Gates Brook and the Stillwater and Quinapoxet Rivers will be obtained from continuous recording devices installed by the USGS.

Sampling at all active logging operations will continue with turbidity samples collected above and below each proposed stream crossing during dry and wet weather prior to the start of any activity to establish baseline conditions, during the installation of all temporary bridges or pole crossings, regularly throughout active logging operations, and after all activity has ceased. Sampling will also occur where timber harvesting is taking place within fifty feet of a stream or steep slopes are present.

Monitoring to assess impacts of active forest management has begun. The monitoring effort utilizes paired subbasin sampling at and near a single forestry site in the Wachusett watershed. Sampling includes monthly dry weather grab sampling and quarterly storm event monitoring using automatic samplers for turbidity, total suspended solids, total organic carbon, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, and total phosphorus. Documentation of tributary flow and precipitation amounts and intensity will also be done. Data will be used to estimate nutrient loading and will be compared to loading estimates from other subbasins across the Wachusett watershed to determine if Division forestry management methods prevent measurable impacts upon stream water quality.

Temperature, dissolved oxygen, pH, and conductivity profiles will be measured weekly from the reservoir at Basin North/Station 3417 in conjunction with weekly or twice weekly plankton monitoring. More frequent profiles will be collected when necessary to document changing conditions in the reservoir. Samples for nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus, and total silica will be collected quarterly at Basin North/Station 3417, Basin South/Station 3412, and Thomas Basin using standard methodologies used in the past.

Movement of water and contaminants through the reservoir remains the focus of significant interest. Sampling of the reservoir surface will continue on a regular basis. Monthly, biweekly, or weekly bacterial transect sampling will be done during ice-free periods to help further understand the effect of avian populations and water movement on fecal coliform levels throughout the reservoir.

APPENDIX A

Results of Quarterly Nutrient Sampling:
Total Phosphorus (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	0.007	0.015	0.006	0.008
MD61	Basin North (M)	0.005	<0.005	0.007	0.008
MD62	Basin North (H)	<0.005	0.019	0.008	0.008
MD26	Basin South (E)	0.008	0.015	0.005	0.007
MD63	Basin South (M)	<0.005	0.018	0.009	0.008
MD64	Basin South (H)	0.006	0.011	0.008	0.008
MD27	Thomas Basin (E)	0.011	0.016	<0.005	0.012
MD65	Thomas Basin (M)	0.011	0.017	0.005	0.013
MD66	Thomas Basin (H)	0.010	<0.005	0.007	0.013

Results of Quarterly Nutrient Sampling:
Ammonia (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	<0.005	<0.005	<0.005	<0.005
MD61	Basin North (M)	<0.005	0.014	<0.005	<0.005
MD62	Basin North (H)	0.005	0.038	0.011	<0.005
MD26	Basin South (E)	<0.005	<0.005	<0.005	<0.005
MD63	Basin South (M)	<0.005	<0.005	<0.005	<0.005
MD64	Basin South (H)	0.006	0.036	0.011	<0.005
MD27	Thomas Basin (E)	<0.005	<0.005	<0.005	<0.005
MD65	Thomas Basin (M)	<0.005	<0.005	<0.005	<0.005
MD66	Thomas Basin (H)	<0.005	<0.005	<0.005	<0.005

Results of Quarterly Nutrient Sampling:
Nitrate (mg/L; MDL = 0.005 mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	0.064	<0.005	<0.005	0.035
MD61	Basin North (M)	0.066	0.023	0.032	0.034
MD62	Basin North (H)	0.072	0.071	0.124	0.033
MD26	Basin South (E)	0.068	<0.005	<0.005	0.036
MD63	Basin South (M)	0.065	0.017	0.006	0.035
MD64	Basin South (H)	0.085	0.071	0.113	0.035
MD27	Thomas Basin (E)	0.082	<0.005	<0.005	0.062
MD65	Thomas Basin (M)	0.082	0.006	<0.005	0.070
MD66	Thomas Basin (H)	0.087	<0.005	0.011	0.076

Results of Quarterly Nutrient Sampling:
Total Kjeldahl Nitrogen (mg/L; MDL = 0.05 mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	0.178	0.161	0.187	0.238
MD61	Basin North (M)	0.195	0.161	0.144	0.244
MD62	Basin North (H)	0.244	0.183	0.140	0.139
MD26	Basin South (E)	0.209	0.178	0.131	0.208
MD63	Basin South (M)	0.208	0.166	0.159	0.194
MD64	Basin South (H)	0.199	0.156	0.135	0.183
MD27	Thomas Basin (E)	0.227	0.180	0.168	0.291
MD65	Thomas Basin (M)	0.214	0.173	0.215	0.205
MD66	Thomas Basin (H)	0.244	0.138	0.170	0.221

Results of Quarterly Nutrient Sampling:
UV254 (A/cm)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	0.057	0.054	0.039	0.042
MD61	Basin North (M)	0.060	0.054	0.043	0.042
MD62	Basin North (H)	0.060	0.057	0.055	0.042
MD26	Basin South (E)	0.067	0.055	0.039	0.045
MD63	Basin South (M)	0.061	0.050	0.037	0.045
MD64	Basin South (H)	0.069	0.060	0.053	0.046
MD27	Thomas Basin (E)	0.165	0.060	0.038	0.110
MD65	Thomas Basin (M)	0.162	0.060	0.039	0.117
MD66	Thomas Basin (H)	0.165	0.040	0.032	0.121

Results of Quarterly Nutrient Sampling:
Silica (mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	2.45	1.11	1.39	2.09
MD61	Basin North (M)	2.59	2.01	2.10	2.06
MD62	Basin North (H)	2.66	3.42	3.87	2.09
MD26	Basin South (E)	2.73	1.20	1.39	2.24
MD63	Basin South (M)	2.52	2.01	1.83	2.05
MD64	Basin South (H)	2.92	3.27	3.15	2.22
MD27	Thomas Basin (E)	3.90	1.26	1.52	4.03
MD65	Thomas Basin (M)	3.88	1.80	1.31	4.22
MD66	Thomas Basin (H)	3.88	1.87	1.75	4.40

Results of Quarterly Nutrient Sampling:
Alkalinity (mg/L)

		Sampling Date			
ID	Sampling Station	05/02/14	07/23/14	10/07/14	12/04/14
MD25	Basin North (E)	6.12	6.98	6.24	5.98
MD61	Basin North (M)	6.02	5.62	5.66	6.14
MD62	Basin North (H)	6.02	6.96	6.58	6.22
MD26	Basin South (E)	6.16	6.86	6.34	6.00
MD63	Basin South (M)	6.16	5.34	5.04	5.96
MD64	Basin South (H)	6.04	7.02	6.56	5.92
MD27	Thomas Basin (E)	6.46	7.30	6.34	5.48
MD65	Thomas Basin (M)	6.36	7.24	6.58	5.80
MD66	Thomas Basin (H)	6.74	4.92	4.90	6.06

APPENDIX B

Mudmat *Glossostigma cliestanthum* in Wachusett Reservoir
Initial Memorandum: August/September 2014
Jamie Carr and Joy Trahan-Liptak, MA DCR Aquatic Biologists

Timeline/Discovery: ESS group biologists collected and identified *Glossostigma cleistanthum* or "mudmat" during a Wachusett Reservoir aquatic plant survey on 8/5/2014. ESS identified mudmat at 17 locations during their point transect survey of Wachusett Reservoir during that week. DCR Aquatic Biologists Jamie Carr and Joy Trahan-Liptak followed up on this effort and identified 37 additional locations with mudmat occurrence throughout the reservoir in August 2014. Conversations with former Natural Heritage Botanist Brian Connelly revealed that Tom Rawinski, a US Forest Service Botanist who lives in Oakham, had made a habit of botanizing the Muddy Brook Cove area of the Wachusett Reservoir. Tom had submitted a report for *Glossostigma* in the Wachusett Reservoir to NHESP in 2010. In an email to Brian dated 9/10/2010, Tom indicated that *Glossostigma cleistanthum* was "thoroughly established all along the cove on either side of the Muddy Brook mouth. It's probably to be found throughout the reservoir." Subsequent phone conversations with Tom confirmed this, as well as the fact that he did not observe the plant at this location during surveys from 2007-2009 (although Tom believed high water may have made it more difficult to observe at that location from shore during those visits).

Background: "There is little definitive information regarding distribution, ecology or invasive potential of *Glossostigma* in North America" (Les et al., 2006). What has been established is that unlike many introduced species which occur in eutrophic waters, *G. cleistanthum* prefers oligotrophic waters (i.e. low in nutrients, alkalinity, and conductivity as well as high water clarity). Consequently, the low nutrient levels, clear water and sandy shorelines of the Wachusett Reservoir provide ideal mudmat habitat.
Mudmat is indigenous to Australia, East Africa, India, and New Zealand. The species was first documented in North America during 1992 in New London County, Connecticut. It has subsequently been documented in additional Connecticut sites as well as Delaware, Maryland, New Jersey, Pennsylvania, and Rhode Island. The species was listed as occurring in Worcester County in the 2011 publication *The Vascular Plants of Massachusetts: A County Checklist*. Tom Rawinski has reported finding mudmat in 3 locations in Massachusetts (personal communication).

Biology: *G. cleistanthum* may be submersed in waters 0.1 to 4m in depth or emergent in saturated substrates. This diminutive aquatic plant spreads by rhizome along the sediment and produces paired spatulate leaves that are generally <25mm long. The preferred substrate appears to be sand; plants have also been observed in mud, silt, and occasionally gravel. Maximum depth of *G. cleistanthum* is likely dependent on water clarity; as the plant prefers full sunlight, but has been reported at depths up to 4m in one location. *G. cleistanthum* is a perennial when submersed (as observed thus far in Wachusett Reservoir) and may remain green under ice throughout the winter. Reproduction takes place via seed as well as vegetatively via rhizome elongation and fragmentation. Seeds are produced by self-pollinating flowers in submersed populations and cross-pollination in emergent populations. Dispersal is via wind and rain, movement of dislodged fruit-bearing plantlets via water currents, and transport of mud via animal vectors (e.g., ducks and geese). Dense patches of *G. cleistanthum* are reportedly capable of producing 23,000 seeds/m^2 and the maximum plant density may reach 25,000 plants/m^2.

Glossostigma species are used in the aquarium trade and, although another species is preferred, the difficulty in differentiating between species of this genus suggests that *G. cleistanthum* is unintentionally utilized in aquariums. As with many introduced species in North America, improper aquarium disposal is therefore a likely vector of infestation.

"Because *G. cleistanthum* grows mainly in low underwater mats, it is extremely difficult to detect until the patch density reaches a conspicuous level of infestation. As a consequence, the species is probably much more widely established than current records would indicate" (Les et al., 2006). The diminutive size and similarity to the native *Elatine* species explains why mudmat was not discovered earlier by DCR or reported from any location by ESS during their 2010 or 2013 Wachusett Reservoir surveys.

Initial observations: On August 12th, 2014 Jamie Carr and Joy Trahan-Liptak observed dense growth of mudmat in the shallow water of the cove behind Gate 22. In this location, mudmat growth was dense within an area of approximately 0.5 acres in size. Moving northwest from that area along the shoreline, mudmat occurrence was documented in a stretch of shoreline over 1 mile long (see map below). Mudmat presence was most often very difficult to detect and most locations had very minimal growth. Dense patches were typically $1ft^2$ to $3ft^2$ in size. In addition, several other small low growing native plants were present in similar or greater density to mudmat growing in the same habitats. These included: small waterwort *Elatine minima* (abundant), quillwort *Isoetes* spp. (common), burreed *Sparganium* spp. (common), Hedge hessop *Gratiola aurea* (infrequent), pipewort *Eriocaulon* spp. (infrequent) and isolated populations of a newly discovered diminutive non native plant identified as Asian waterwort *Elatine ambigua* (three locations: Andrews Harbor, Malagasco Brook Cove, and Gates Brook Cove). In addition, mudmat was found growing along the bottom below tall stands of native claspingleaf pondweed *Potamogeton perfoliatus*.

Mudmat growth in Wachusett Reservoir has been observed in areas 0.5 - 8.5 feet in depth. Dense growth was limited to areas that were between 3 and 6 feet in depth and had silt or fine sand substrate. In the majority of locations, dense patches were rare and small in size. Even when not readily apparent, mudmat could be found if one looked long enough and hard enough.

Initial conclusions: Wachusett Reservoir appears to provide the preferred habitat for mudmat and it has become well established within the littoral zone. It appears that mudmat has been present for a significant period of time, with first documentation occurring 5 years ago and initial colonization likely much earlier. ESS documented mudmat in the western part of the mid basin, in South Bay and mid-reservoir. Subsequent DCR surveys confirm that mudmat is very well spread out and present as a widespread population throughout the reservoir (see map Figure 1). These observations simply document mudmat presence and are not a complete map of it distribution. Irrespective of cost, no management options that we are aware of are currently available that would allow mudmat to be removed, smothered, treated or eradicated from the extensive sections of shoreline where growth has been documented thus far. Observing locations which currently support minimal mudmat growth over the next few years may provide insight as to the potential for spread of this plant and whether or not it is still actively colonizing new habitats or has already filled most of the available habitat.

Potential water quality implications: There are currently no documented examples of water quality impacts associated with mudmat growth in North America that we are aware of. Most negative environmental impacts which are speculated from mudmat growth relate to presumed negative impacts on rare native plant species. Observations of mudmat growth in the Wachusett Reservoir in 2014 do not suggest that the species is overtaking or prohibiting growth of native plant species on a significant level. Ongoing monitoring of mudmat may help determine the species' potential impacts to the reservoir ecosystem; however, based on current observations and research, mudmat does not appear to pose a threat to water quality at the Wachusett Reservoir.

Figure 1: Current distribution map of potential habitat suitability and known mudmat locations in Wachusett Reservoir

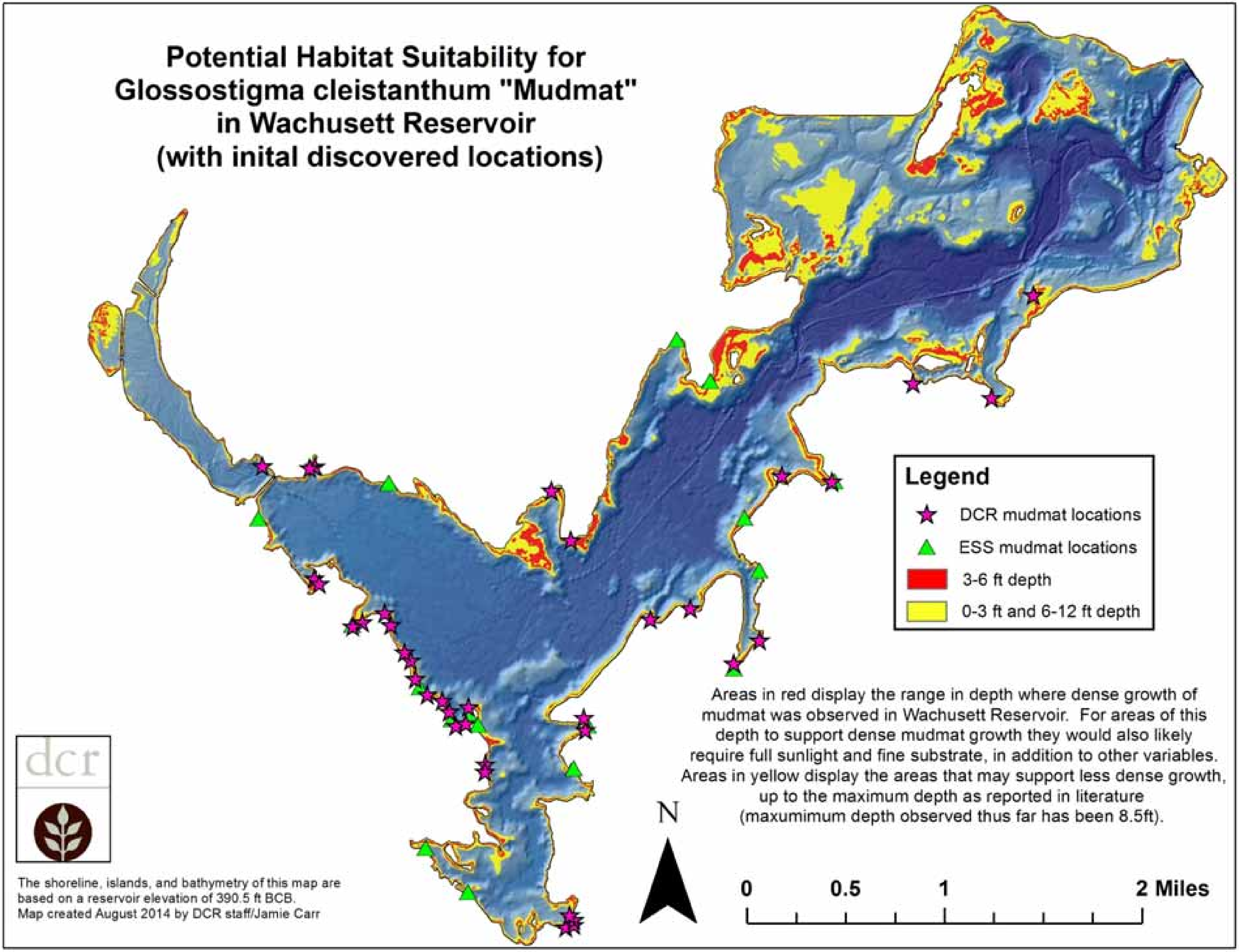


Photo Documentation:

Figure 2 ***Glossostigma cliestanthum*****/mudmat**

Figure 3 Native ***Elatine minima*****/waterwort (left) and** ***Glossostigma cliestanthum*****/mudmat (right)**

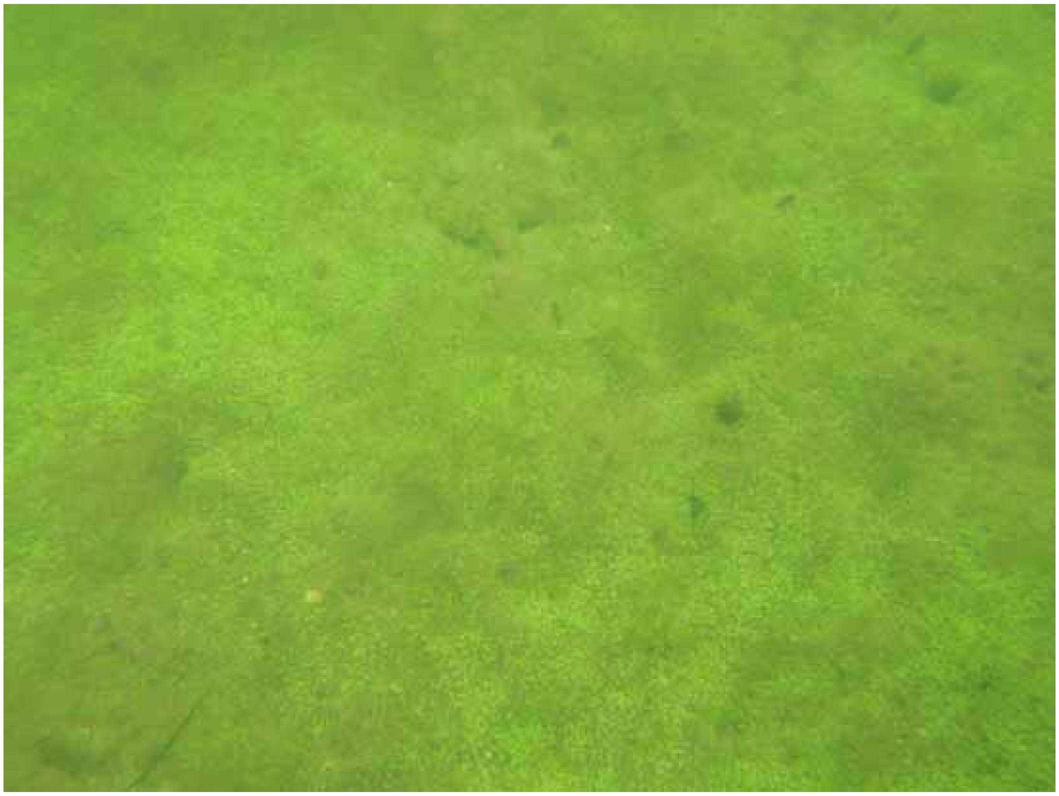


Figure 4 Highest mudmat density observed: Southeast corner of Pine Cove behind Gate 22

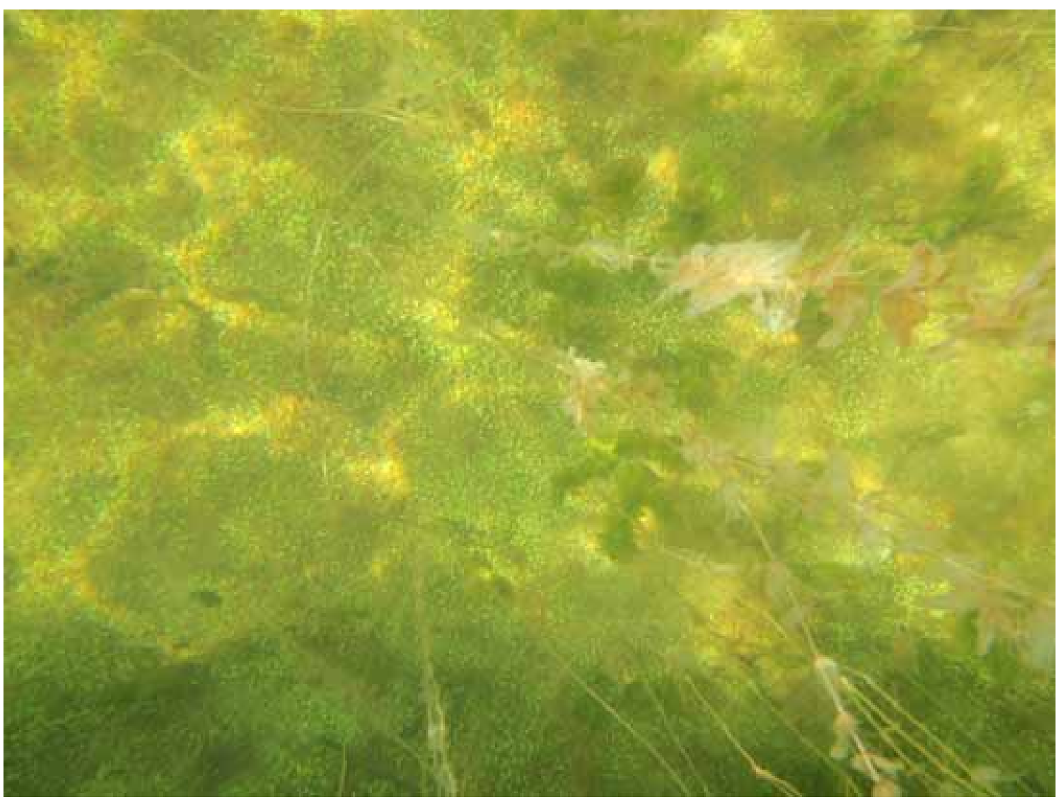


Figure 5 Mudmat growing beneath *Potamogeton perfoliatus*

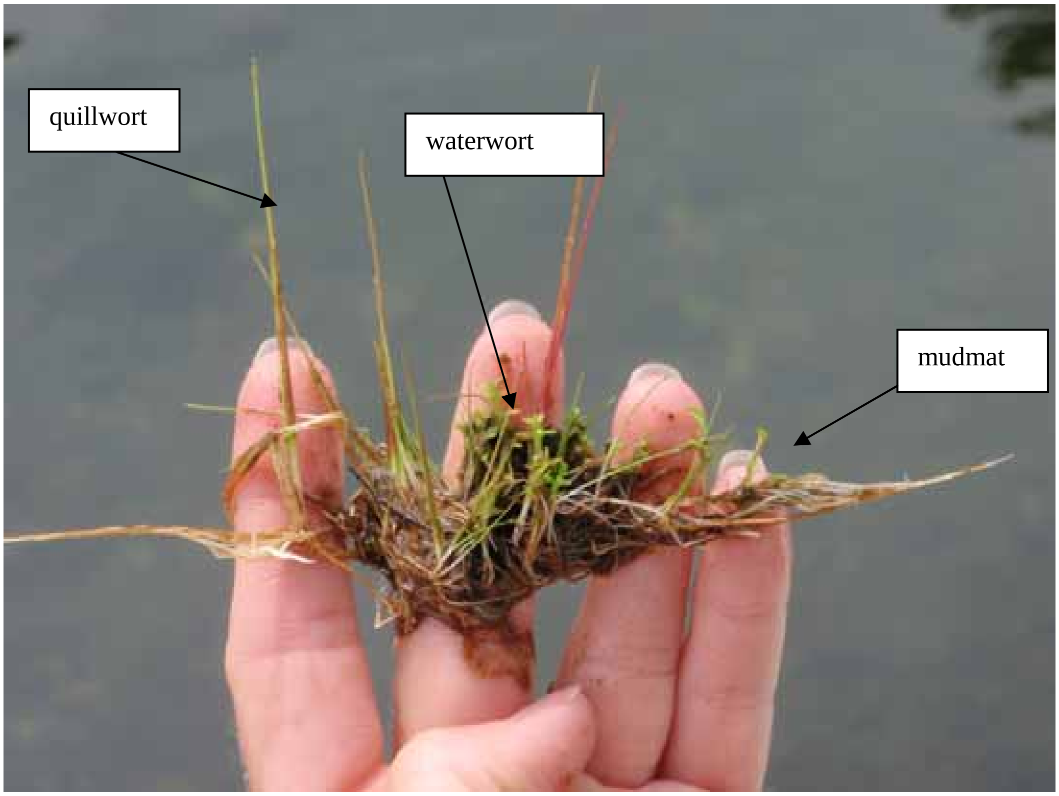


Figure 6 Common littoral benthic plant assemblage

Figure 7 Moderate mudmat growth with native *Elatine minima*/waterwort interspersed

Figure 8 Sparse mudmat growth limited by substrate

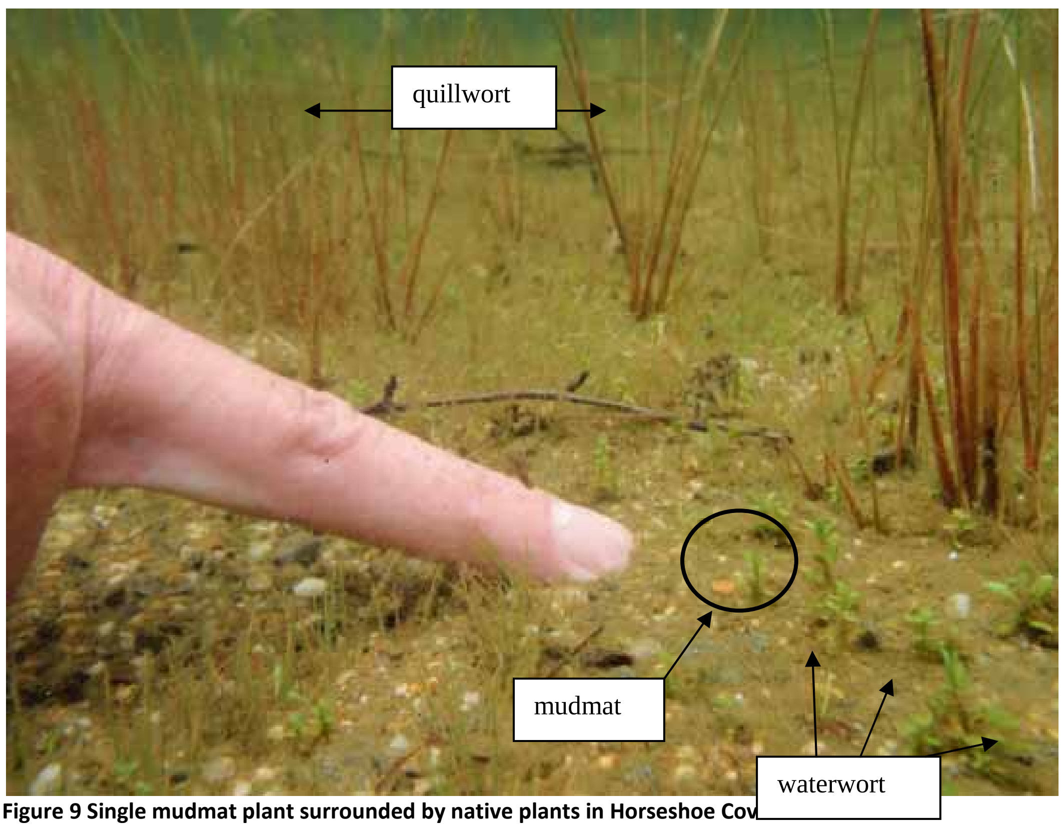


Figure 9 Single mudmat plant surrounded by native plants in Horseshoe Cov

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All photos 2014 by MA DCR Jamie Carr and Joy Trahan-Liptak